Geotechnical Properties of Selected Pleistocene, Silurian, and Ordovician Deposits of Northeastern Illinois

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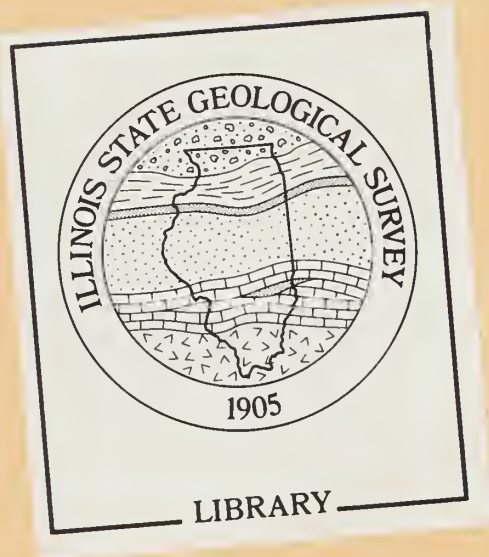A. M. Graese
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ABSTRACT

Large quantities of detailed geotechnical data on the bedrock and glacial drift in northeastern Illinois were collected and compiled as part of the investigation for a suitable site for the proposed Superconducting Super Collider (SSC). The database includes (1) preexisting information such as stratigraphic data obtained from boreholes, strength test results, and observations and experiences from tunneling and construction of underground chambers in the region; and (2) new data from investigations conducted specifically for the SSC project, including studies of additional boreholes; hydrogeologic studies of water levels and in situ hydraulic conductivity; strength testing of rocks and soils; assessment of rock hardness and joint strength, and joint characterization; determination of laboratory and in situ sonic velocities; and rock mass classification and measurement of in situ stress magnitude and direction. This extensive database was used to characterize rock mass conditions and tunneling advance rates. Test results and construction experience in bedrock indicate that rock quality is good, tunneling conditions are favorable, and little or no support is required. Chambers with spans of 63 feet have previously been excavated in the dolomite bedrock, but studies for the SSC project shows that spans up to 125 feet are possible.

Information gained from several successful underground construction projects in the Chicago and Milwaukee areas (where geologic conditions are similar) also indicate that construction of tunnels and chambers within the bedrock of northeastern Illinois is practical and that construction conditions are predictable.

The geotechnical and stratigraphic data summarized in this report should be useful for siting future construction projects in glacial and bedrock materials in northeastern Illinois.

INTRODUCTION

An extensive program of geotechnical studies was begun in 1983 by the Illinois State Geological Survey to determine the geological and environmental suitability of a proposed site for the Superconducting Super Collider (SSC) in Illinois. The program involved detailed geological and geotechnical investigations of an area in northeastern Illinois that included Kane County and parts of Cook, De Kalb, Du Page, Kendall, and Will Counties (figs. 1 and 2). Preexisting information was compiled and new research was conducted. The preexisting information provided a baseline for stratigraphic, hydrogeologic, and geotechnical characteristics of the regional surficial and bedrock materials. Site-specific exploration and laboratory testing confirmed and refined the preliminary conclusions reached on the basis of the preexisting data on the SSC site area. The scope of the these feasibility studies is comparable to that of the the preconstruction investigations for the Tunnel and Reservoir Plan (TARP) east of the proposed SSC area. Data resulting from the SSC and TARP site investigations and from TARP construction experiences have considerably augmented the database on regional geology and geotechnical characteristics for a large area of northeastern Illinois (fig. I). Because TARP data is difficult to obtain, much of it has been included in this publication.

Descriptions of the SSC siting investigations and summaries of their results are presented in Kempton et al. (1985, 1987a, and 1987b), State of Illinois (1987), Curry et al. (1988), Conroy et al. (1988), Vaiden et al. (1988), and Graese et al. (1988). TARP drilling information and laboratory test results are found in Buschbach and Heim (1972) and Harza Engineering (1972, 1975a, and 1983). Summaries of many of the findings are also included in the State of Illinois SSC Proposal, Volume 3 (1987), and in Conroy et al. (1988).
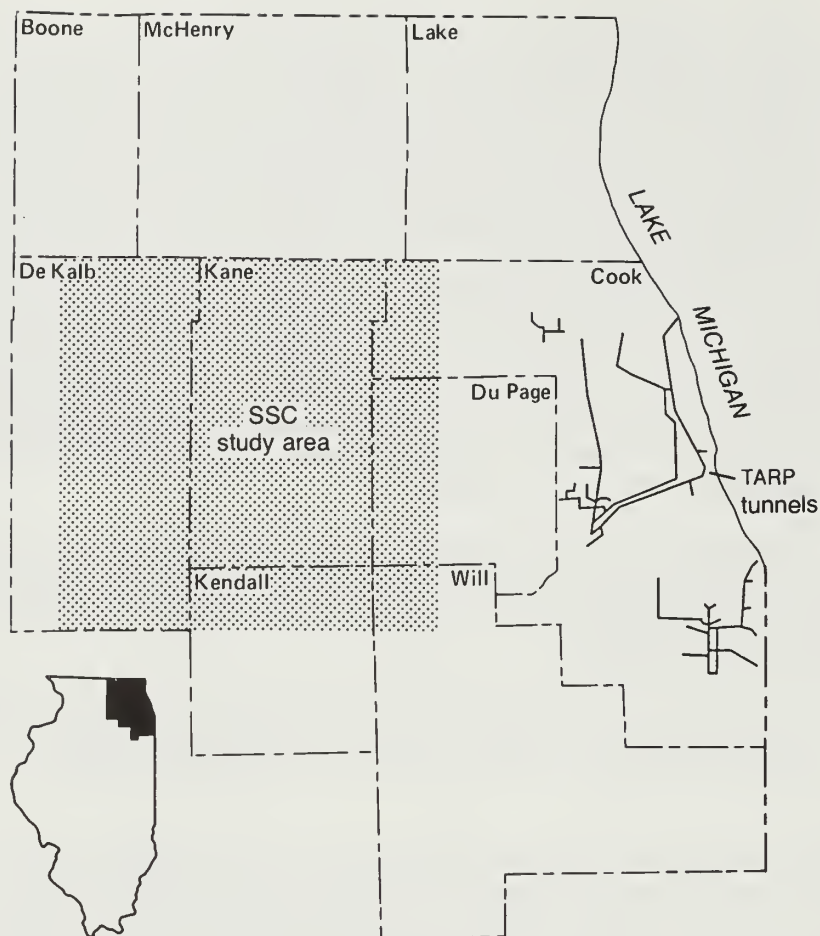
Figure 1 Location of the SSC study area and TARP tunnels in northeastern Illinois.

SOURCES OF PREEXISTING DATA FOR THE SSC STUDY AREA

The preexisting database for the proposed SSC area consists of data from 7,700 water wells and 78 engineering borings (fig. 3). The water well borings provide information on the bedrock stratigraphy and the topography of the bedrock surface. The engineering boreholes provide information about geologic materials (mostly glacial deposits) and their engineering properties. Samples and cores from more than 1,500 wells and borings in the SSC area are available for study at the ISGS. Forty-two maps showing geology, land use, physical setting, conservation and preservation, cultural features, and wells and borings in the SSC study area are included in Hines (1986).

Local Tunneling Experience

The Chicago Tunnel and Reservoir Plan (TARP) is a storm-water collection and storage system of the Metropolitan Sanitary District of Greater Chicago (MSD) that provides pollution and flood control in the Chicago Metropolitan Area. TARP utilizes a system of deep tunnels excavated in rock 200 to 350 feet deep; when completed, TARP will be the largest underground public works project ever constructed (fig. 4). Studies for TARP were begun more than two decades ago, and construction began in 1975. Phase I of the plan was recently completed on time and under budget, with a construction cost of approximately $1.2 billion.
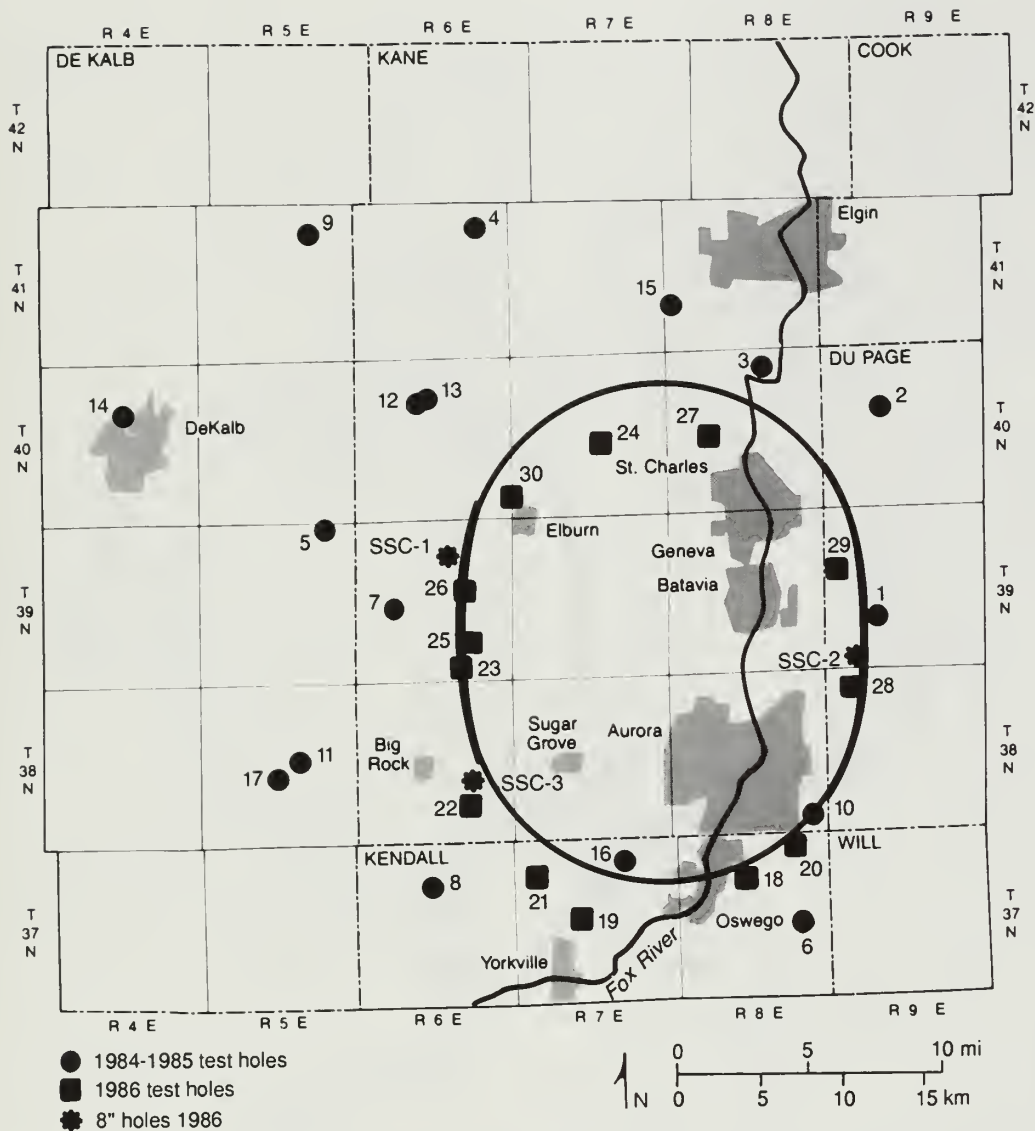
Figure 2 Test-hole locations in the SSC area.

More than 90 miles of tunnels were safely and economically excavated in rock using tunnel boring machines (TBMs) as part of TARP and related sewer construction. These projects also involved excavation of more than 280 shafts (5.5 to 39.5 ft in diameter) and construction of four large underground caverns (two are 63 feet wide, 96 feet high, and 310 feet long; the other two are 66 feet wide, 59 feet high, and 203 feet long).

Preconstruction Investigations

The following preconstruction exploration programs and studies for TARP were conducted in four phases between 1967 and 1976 (Harza Engineering 1983):

- a literature research and review, utilizing information from the Illinois State Water Survey, the Illinois State Geological Survey, quarry operations, and federal agencies: engineering reports
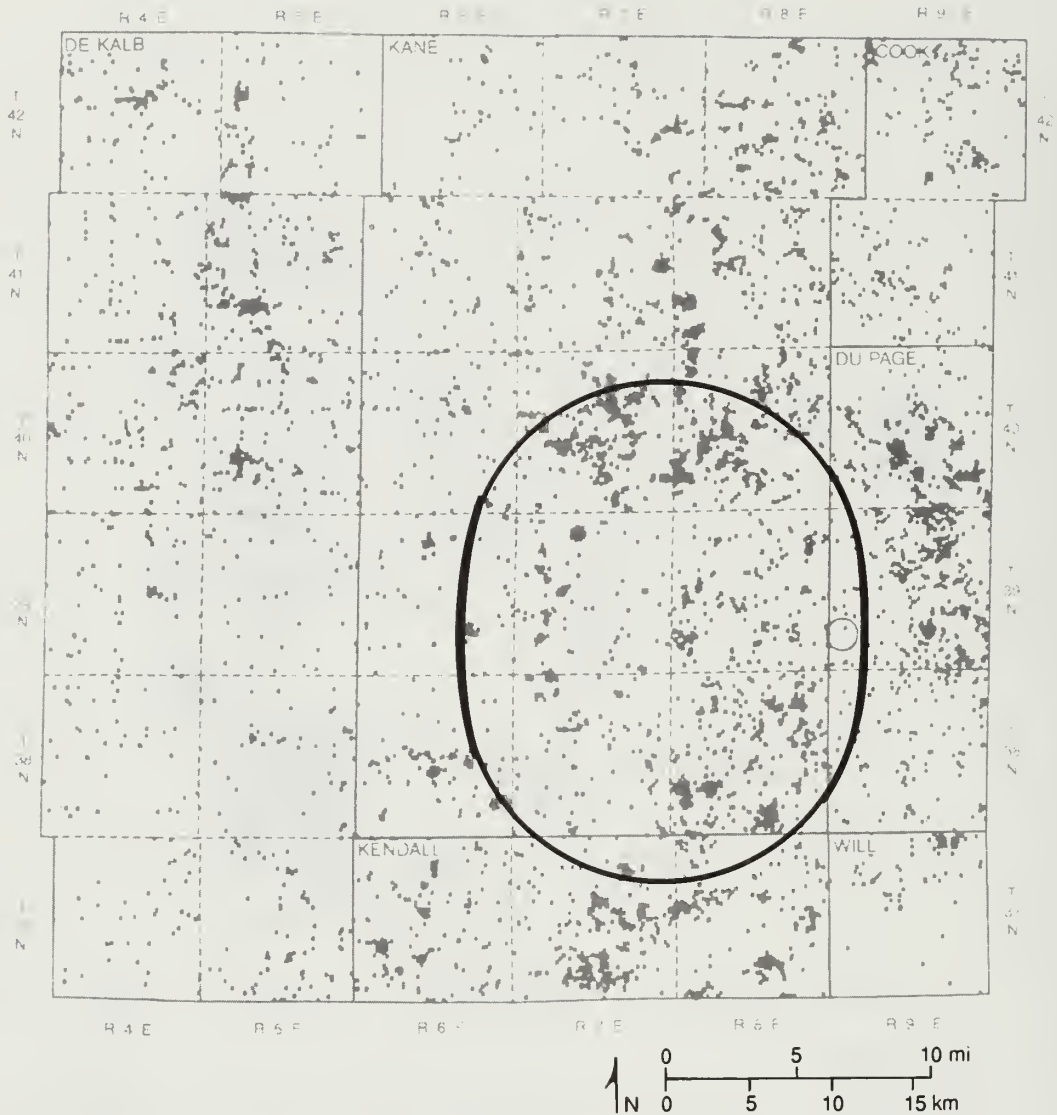
Figure 3 Locations of all wells and drill holes in SSC study area.

from previous studies were reviewed and integrated with the results of the preconstruction investigations;

- compilation of data and experience gained from previous rock tunneling experience in the Chicago area (such as data on excavation characteristics, jointing, stability, and groundwater inflow);
- geologic mapping of quarries and existing tunnels;
- geophysical surveys (420 miles of refraction and reflection seismic survey profiling);
- borings (208) in glacial materials along the Mainstream System at each drop shaft and construction shaft site, each terminating a few feet in the bedrock;
- rock drilling of 230 cored holes, with a combined total of 144,895 linear feet; of these, 157 were drilled along the Mainstream tunnel alignment; additional core drilling was conducted during construction to investigate rock quality in certain critical areas, or to install instrumentation;

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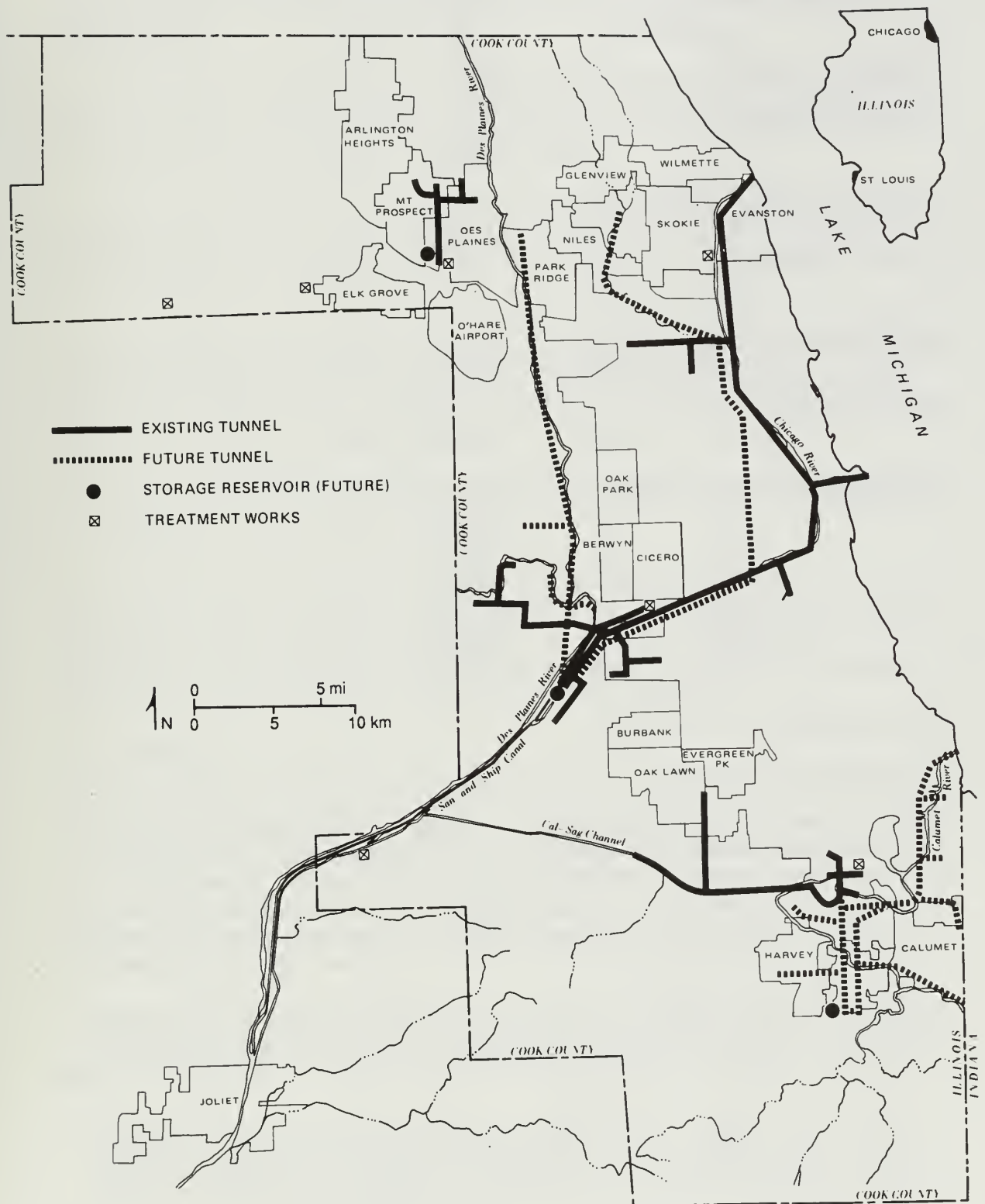
Figure 4 TARP tunnels in the Chicago area (Harza 1987).

Table 1 Summary of data on joint orientations and spacing in northeastern Illinois.

Data source	NE SET Average spacing (dir)	(ft)	NW SET Average spacing (dir)	(ft)	NE & NW SETS Average spacing (ft)
Quarries (Foote 1982)					
	N47°E	5-10	N50°W	3-10	--
Calumet Tunnels (Shuri and Kelsey 1984)					
	N40°E	--	N50°W	--	--
TARP Tunnels (Weiss-Malik and Kuhn 1979)					
	N40°E	--	N60°W	--	--
SSC Borehole F-8 (Kempton et al. 1987a)					
	N30-60°E	3-7	N35°W	3-7	--
McCook Quarry (Harza 1975a)					
	N40-60°E	50-500	N35-60°W	1-500	--
TARP Mainstream Tunnels (Harza 1984)					
	N38°E	341	N47°W	225	135
	N50°E	768	N53°W	167	137
	N60°E	318	N45°W	85	67
	N65°E	--	N62°W	--	--
	N42°E	171	N55°W	190	90
	N38°E	290	N60°W	186	113
	N26°E	91	N46°W	21	17
	N50°E	266	N50°W	129	87
TARP 8-foot-diameter tunnel (ISGS Study)					
	--	--	--	--	20-25

- sampling and testing in all exploration holes; standard penetration tests were conducted in soil borings using a split-spoon sampler, and samples from these tests were laboratory-tested for Atterberg limits, unconfined compression, moisture content, and dry density;

- hydrogeologic studies, including pressure testing of cored holes to determine hydraulic conductivity; pumping tests; bailing tests; recharge and aquifer tests; water-level monitoring in more than 100 exploration boreholes converted to observation wells; and measurements of water quality and temperature;

- geophysical borehole logging of 41 exploration core holes and three 8-inch rotary holes: evaluation of the resulting geophysical data included determination of estimated porosity, specific gravity, dynamic modulus of elasticity, Poisson's ratio, and compressional and shear wave velocities in the various rock strata;

- laboratory testing of rock core samples, including determination of unconfined compressive strength, tensile strength, porosity, natural moisture content, specific gravity, static and dynamic modulus of elasticity, abrasion resistance, wetting, drying, and soaking behavior, creep, slake durability, and chemical and petrographic analyses.

Results of these investigations indicated that joint orientations were similar to those found in other projects; however, joint spacing varied widely, from averages of about 135 feet in some

areas to as little as 17 feet in one branch tunnel (table 1). Little information on the spacing of steeply dipping to vertical joints could be determined from vertical core holes, which rarely intersect such joints.

The geologic conditions encountered in two pump house caverns confirmed the interpretations derived from detailed surface and subsurface investigations in the site area. Lithologic contacts and characteristics of the rock units closely resembled those anticipated in the design studies. No change in the pattern or frequency of joints was noted.

The long axes of the TARP caverns were oriented to bisect the major northeast and northwest joint sets as determined from angle holes in the pump house area and from joints mapped in McCook Quarry and the Southwest Intercepting Sewer 13A (table 1). This orientation proved to be ideal with respect to the joint pattern.

Low to very low permeability of the rock mass, indicated by earlier water pressure-test data in the drill holes, was confirmed during excavation of the two pump houses. Very low to negligible amounts of initial inflow, 16 gpm and 30 gpm for the north and south pump houses, respectively, were encountered despite the high potentiometric head, 200 to 300 feet above the invert (floor) of the pump houses (Harza 1983).

Because of the excellent rock conditions encountered, the contractor was able to complete all cavern excavation several months ahead of schedule.

EXPLORATION AND LABORATORY TESTING FOR SSC SITING

Field investigations were conducted in all quarries in the area to document glacial and bedrock geology as well as geotechnical characteristics such as jointing, the nature of the glacial/bedrock contact, and the behavior of mined materials. Most samples were obtained through the SSC drilling program, but some were collected from quarries.

Field Exploration

Test hole drilling Thirty-three exploratory test holes having a combined footage of 16,734 linear feet were drilled specifically for the SSC siting study (fig. 2). Thirty of the test holes were NQ-wireline holes (designated F-1 through F-17 and S-18 through S-30), and three were 8-inch diameter rotary holes (designated SSC-1, 2, and 3) drilled to a depth of about 1,000 feet to verify seismic surveys, perform sonic wave velocity studies, and install piezometers. All but three holes were drilled vertically. Angle holes (F-8, S-25, S-29) were inclined 30° from vertical to intersect vertical joints. In situ stress measurements were determined in the bedrock in S-26 and S-28 (Haimson 1987).

Detailed geologic logs of each hole were prepared. Summary logs for holes F-1 through F-9 are provided in Kempton et al. (1987a), F-10 through F-17 in Kempton et al. (1987b), S-18 through S-30 in Curry et al. (1988), and SSC-1 through SSC-3 in Vaiden et al. (1988). Information and materials compiled from the test holes include

- stratigraphic data on the soil and rock units encountered during drilling;
- results of standard penetration tests (sampling, and blow count determinations in the soil units, using a split spoon sampler);
- samples of rock units for laboratory testing;
- determinations of core recovery, Rock Quality Designation (RQD), and drilling rates in rock;

- in situ tests, including in situ stress determination by hydrofracturing, pressure testing to determine permeability, and pumping tests;
- geophysical borehole logging;
- piezometric heads.

Borehole logging Downhole geophysical logging conducted in the test holes included gamma-gamma/density, neutron, spontaneous potential, resistivity, natural gamma, temperature, and caliper logging. Summaries of results are found in each drilling report (Kempton 1987a and 1987b, Curry 1988, and Vaiden 1988). Sonic wave velocity measurements made in the large-diameter boreholes (SSC-1 through SSC-3) were used to calculate the in situ dynamic moduli values.

In situ testing The following in situ tests were made in boreholes:
- standard penetration tests (split-spoon samples taken at 5-foot intervals in soil units);
- permeability tests (including 1,755 pressure tests conducted in 351 test intervals to help characterize the in situ hydraulic conductivity of the rock units; packer test data for test holes described in Kempton et al. (1987a and 1987b) and Curry et al. (1988) are presented in tables and graphic summary plots;
- hydrofracture tests, conducted in two boreholes (fig. 2, boreholes 26 and 28) to determine in situ rock stresses; procedures, results, and conclusions based on the tests are included in a separate report (Haimson 1987);
- a pumping test, conducted in test hole SSC-1, to measure the hydraulic conductivity and transmissivity of the St. Peter Sandstone aquifer underlying the Platteville Group; results of the pump test are given in Vaiden et al. (1988).

Laboratory Testing and Analyses

The following laboratory tests and analyses were performed specifically for the SSC siting study: (1) clay mineral analyses; (2) soil classification tests (soil moisture content, dry and moist density, grain-size distribution); (3) rock strength tests (confined and unconfined compressive strength, axial and diametral point load, Brazilian indirect tensile, direct shear on joints); (4) rock specific gravity and natural moisture content; (5) compressive wave velocity; (5) hardness tests (Schmidt, Taber Abrasion, Shore, Total Hardness); and (6) slake durability tests. Results of these tests and analyses are summarized in Kempton et al. (1987a,b) and Conroy (1988).

New tests presented in this publication include (1) consolidation tests on clay layers in the Galena and Platteville Groups, and (2) direct shear strength measurements on the joint planes found in the Galena and Platteville Groups.

In addition, tunnel boring machine (TBM) performance evaluation was made by the Robbins Company on the basis of unconfined compressive strength, point load, density, and indentation tests of selected rock samples from the proposed SSC site. A preliminary TBM performance was evaluated by Atlas Copco Roctec, Incorporated, using point load tests and Cerchar Abrasivity test.

STRATIGRAPHY

In northeastern Illinois, glacial deposits (fig. 5) generally overlie Paleozoic bedrock (fig. 6) of Silurian and Late Ordovician age. The areal distribution of surficial glacial deposits in the SSC study area is shown in figure 7 and the areal distribution of bedrock units at the bedrock surface in the SSC study area is shown in figure 8.

Overburden/Soil Units

The overburden materials in northeastern Illinois consist largely of glacial drift (fig. 5). Deposits are heterogeneous, interbedded, and commonly discontinuous. The principal categories of materials are *glacial till*, a compact, heterogeneous mixture of clay, silts, sands, gravels, and boulders; *glacial outwash*, predominantly loose to compact silty sands and sandy silt interlayered in places with gravelly sand and clayey silt; and *lacustrine sediments*, generally soft to stiff fine-grained materials ranging from fine sandy silts to clayey silts deposited in lakes.

Other materials (typically less than 10 feet thick) found in some places are Recent *alluvium*, loose to compact silts, silty sands, and clays; *loess*, loose to compact clayey silt (wind-blown deposits); *organic-bearing sediments*, generally clayey silts containing up to 5 percent organics (small, thin deposits of peat occur locally at the surface and occasionally in the subsurface); and *colluvium* and *topsoil*, a thin veneer of loose, reworked drift deposits, insignificant in terms of thickness.

SYSTEM	SERIES	STAGE	Formation Member		Graphic Log	Genetic Interpretation of Materials and Description
QUATERNARY	HOLOCENE		Cahokia Fm			Alluvium — sand, silt, and clay deposited by streams
			Grayslake Peat			Peat and muck, often interbedded with silt and clay
			Richland Loess			Loess — windblown silt and clay
			Equality Fm			Lake deposits — stratified silty clay and sand
			Henry Fm			Outwash — sand and gravel
	PLEISTOCENE	WISCONSINAN	Wedron Fm	Wadsworth		Till — yellowish brown to gray silty clay loam
				Haeger		Till — yellowish brown loam; extensive, thick basal sand and gravel
				Yorkville		Till — yellowish brown to gray silty clay loam
				Malden		Till — yellowish brown to brownish gray loam to clay; extensive basal sand and gravel west of the Fox River
				Tiskilwa		Till — pinkish brown or grayish brown clay loam
		SANGAMONIAN	Peddicord Fm			Lake deposits — pinkish brown to gray stratified sand, silt and clay
			Robein Silt			Buried soil developed into alluvium, colluvium or bog deposits — organic rich silt, sand and clay.
			Berry Clay			Accretion-gley — clay, silt and sand
		ILLINOIAN	Pearl Fm			Outwash — sand and gravel
			Glasford Fm	Esmond		Till — gray silty loam
				Oregon		Till — light brown to pink sandy loam and loam
				Fairdale		Till — brown loam to clay loam
				Herbert		Till — pink sandy loam, locally contains boulders
				Kellerville		Till — brown loam

Figure 5 Stratigraphic column of surficial deposits in northeastern Illinois.

SYSTEM	SERIES	GROUP	FORMATION thickness (in feet)	GRAPHIC LOG	DESCRIPTION
QUATERNARY	HOLO-CENE		Grayslake Peat (0-15)		Peat and muck
			Richland Loess (0-5)		Silt loam, massive
			Equality (0-35)		Sand, silt and clay, laminated
	PLEISTOCENE		Henry (0-70)		Sand and gravel, stratified
			Wedron (0-250)		Till, sand and gravel, laminated sand, silt and clay
			Peddicord (0-35)		
			Robern Silt (0-28)		Sand, silt and clay, laminated
					Organic-rich silty clay
			Glasford-Banner (0-375)		Till, sand and gravel, laminated sand, silt and clay
SILURIAN	ALEXAN-DRIAN		Kankakee (0-50)		Dolomite, fine grained
			Elwood (0-30)		Dolomite, fine grained, cherty
			Wilhelmi (0-20)		Dolomite, fine grained, argillaceous; shale, dolomitic
ORDOVICIAN	CINCINNATIAN	Maquoketa (undiff.)	(0-210)		Shale, dolomitic; dolomite; fine to coarse grained, argillaceous
	CHAMPLAINIAN	Galena	Wise Lake (120-150)		Dolomite, some limestone, fine to medium grained
			Dunleith-Guttenberg (35-55)		Dolomite, fine to medium grained, cherty
					Dolomite, fine to medium grained with red brown shaly laminae
		Platteville	Quimbys Mill-Nachusa (50)		Dolomite, fine to medium grained, slighty cherty
			Grand Detour-Mifflin (43)		Dolomite, fine to medium grained, argillaceous
			Pecatonica (38)		Dolomite, fine to medium grained, cherty, sandy at base
		Ancell	Glenwood St Peter Ss (60-520)		Sandstone, poorly sorted; silty dolomite and green shale
					Sandstone, white, fine to medium grained, well sorted
	CANAD-IAN	Prairie du Chien (undiff.)	Shakopee New Richmond Oneota (0-400)		Dolomite, fine grained
					Sandstone, fine to medium grained
					Dolomite, fine to coarse grained, cherty
CAMBRIAN	CROIXAN		Eminence (20-150)		Dolomite, fine to medium grained, sandy, oolitic chert
			Potosi (90-225)		Dolomite, fine grained, trace sand and glauconite
			Franconia (75-150)		Sandstone, fine grained, glauconitic; green and red shale
			Ironton-Galesville (155-220)		Sandstone, fine to medium grained, dolomitic
			Eau Claire (350-450)		Sandstone, fine grained, glauconitic; siltstone, shale, and dolomite
			Mt Simon (1400-2600)		Sandstone, white, coarse grained, poorly sorted
PRECAMBRIAN					Granite, red

Figure 6 Statigraphic column of bedrock and drift units in northeastern Illinois.
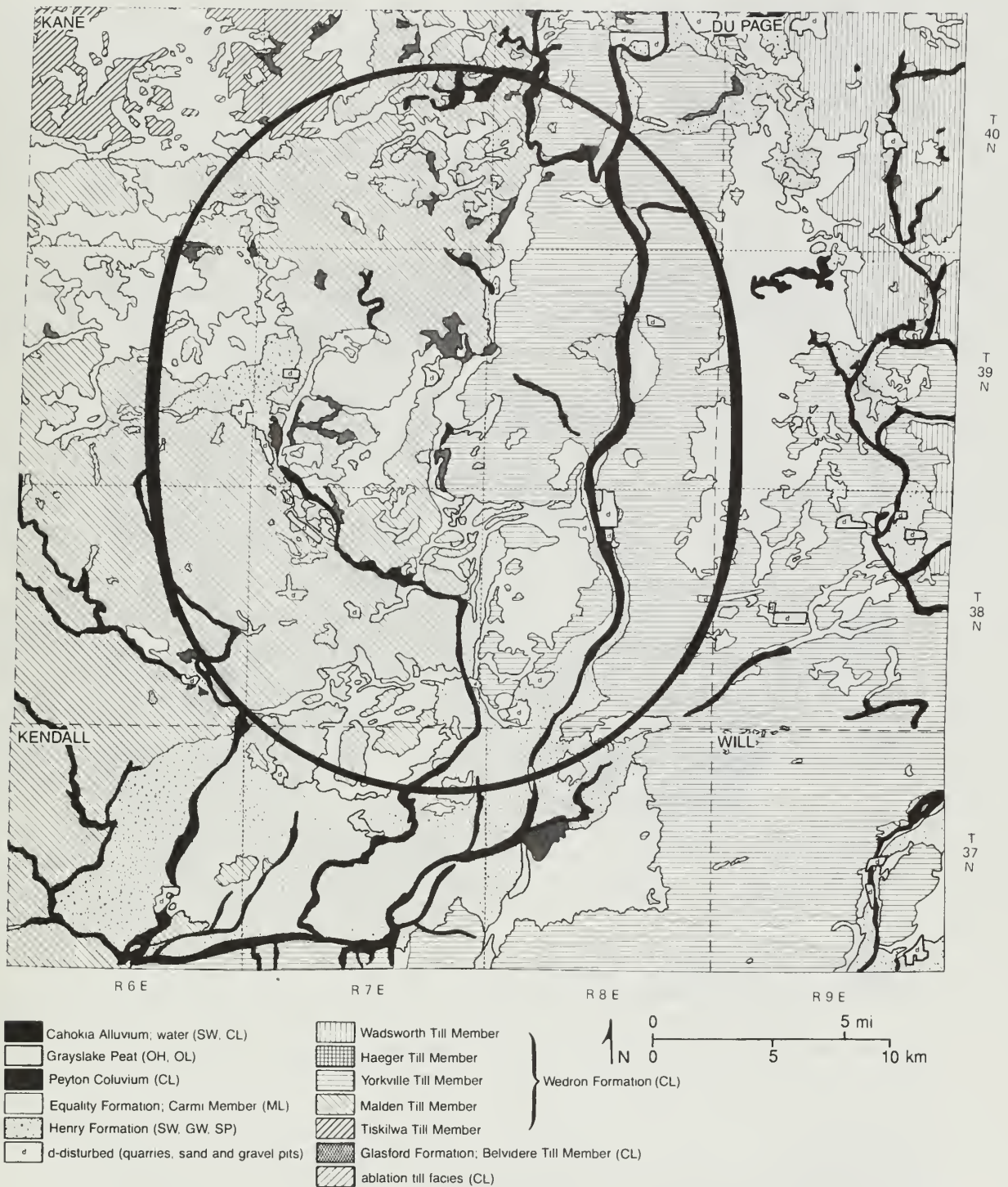
Figure 7   Areal distribution of surficial deposits in the SSC study area.

Richland or Peoria Loess   These units mantle much of the study area characterized as gently sloping; on most moraines or on flood plains the units are thin or absent. The Richland Loess covers the Wisconsinan-age Wedron Formation, whereas the Peoria Loess covers Illinoian-age sediments or bedrock (Willman and Frye 1970). Each loess is usually less than 5 feet thick and is modified by soil-forming processes.
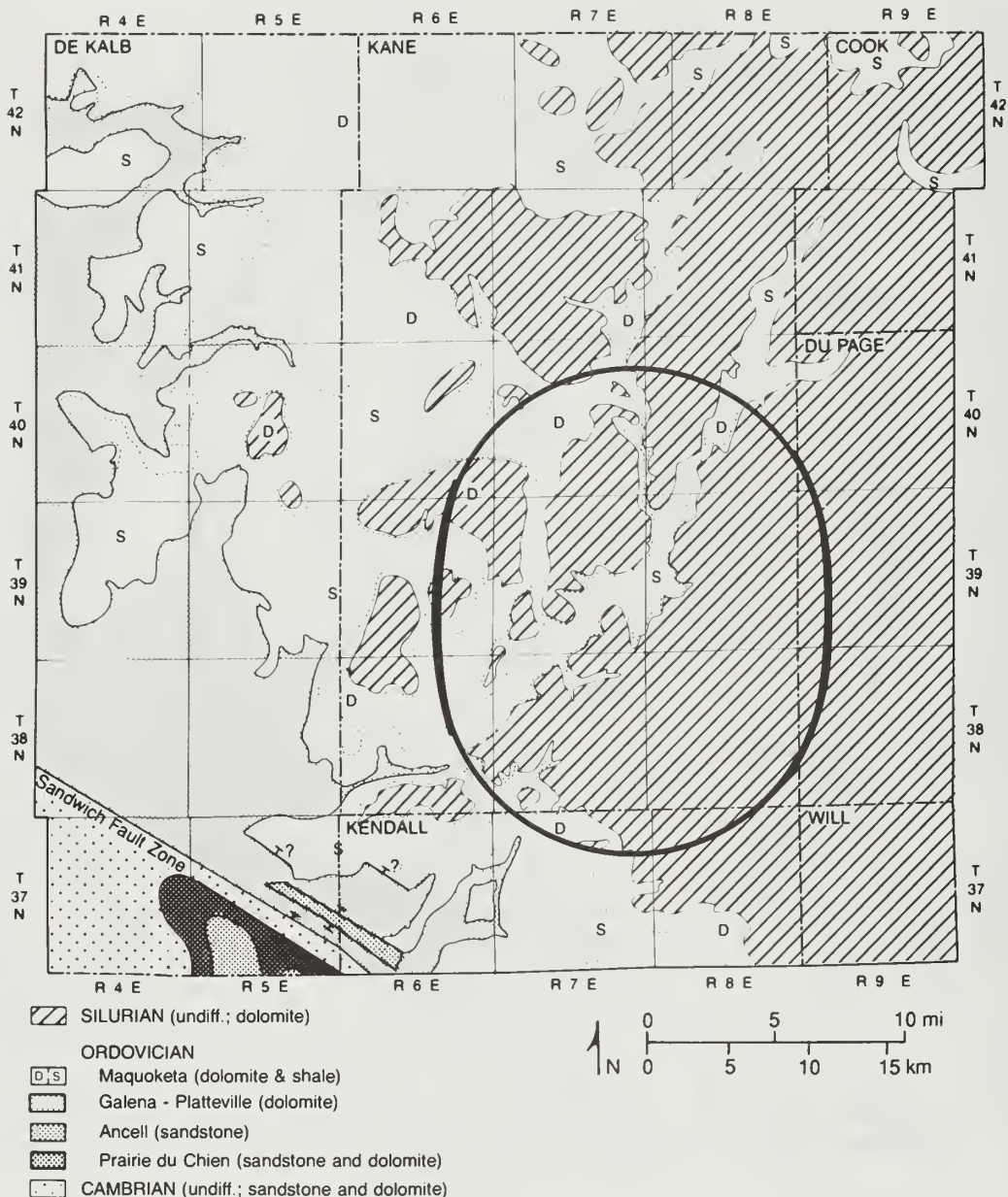
Figure 8 Areal distribution of bedrock units at the bedrock surface in the SSC study area.

Cahokia Alluvium This is the formation name for Holocene deposits in the flood plains and channels along modern rivers. The alluvium is generally composed of silt that contains discontinuous sand and gravel lenses; in the area it may be less than 10 feet thick. The Cahokia overlies Henry and Equality deposits in many places.

Equality Formation The Equality is composed of sediments deposited in lakes formed during the melting of Wisconsinan glaciers. The deposits consist mainly of laminated silt and clay. Lacustrine deposits within till units or below the Henry Formation are not considered Equality Formation; instead, they are mapped as part of the formation in which they occur (Willman and Frye 1970). The Equality Formation is as thick as as 35 feet in places.

Henry Formation This formation consists of glacial outwash deposits (mostly sand and gravel) up to about 70 feet thick. The Henry is found at or near ground surface and in some places is overlain only by loess, alluvium, colluvium, and lacustrine deposits. Sand and gravel deposits covered by another formation are considered part of the overlying formation, not part of the Henry. The Henry Formation may vary from thin, well-sorted, sandy, sheetlike deposits to hills of poorly sorted silt, and gravel; few of these hills (generally ice-contact deposits formed within or under the glacier) are found in the SSC area. Several of these hills are prominent kames in the Elburn Complex. Henry and Equality Formation deposits are commonly interbedded.

Wedron Formation In some places as thick as 270 feet, the Wedron consists chiefly of till interbedded with outwash sand and gravel and lacustrine silt and clay. Five principal till members—in descending order, the Wadsworth, the Haeger, the Yorkville, the Malden, and the Tiskilwa—have been identified in the Wedron and mapped throughout the region.

Wadsworth Till Member is mapped primarily on the basis of its association with the prominent West Chicago Moraine. Schmitt (1985) indicates that the Wadsworth Till is identical to the Yorkville in particle-size distribution, lithic heterogeneity, clay mineralogy, and engineering properties. The Wadsworth is generally less than 50 feet thick along the West Chicago Moraine; it overlies thick sequences of sand and gravel, lacustrine sediment, and a till having variable texture that is interpreted as Haegar Till Member (Hansel and Johnson 1986).

Haeger Till Member, found in the northeastern corner of the SSC study area, is characterized as a sequence of bouldery and cobbly sand and gravel as thick as 60 feet in places, overlain by loam till about 25 feet thick. The Haeger pinches out to the south. Hansel and Johnson (1986) believe that the basal outwash is continuous with the outwash extending beneath and west of the West Chicago Moraine. Below the West Chicago Moraine, the Haeger has been interpreted to occur beneath the Wadsworth Till Member; the character of these materials is similar to that of some units assigned to the Malden Till Member, which underlies Fermilab (Landon and Kempton 1971).

Yorkville Till Member, a gray till consisting of 45 percent clay, 45 percent silts, and 10 percent sand (Kemmis 1981) overlies the Malden or Tiskilwa Till Member. Its color varies from brown or grayish brown where oxidized to dark gray where unoxidized. The Yorkville is more than 50 feet thick in places, but generally is 20 to 30 feet thick.

Malden Till Member is the most lithologically and mineralogically heterogenous till member in the area. In comparison to the Tiskilwa it is relatively thin, averaging little more than 35 feet thick. The Malden usually is associated with stratified gravel, sand, and silt deposits.

Tiskilwa Till Member, the thickest drift unit, is as thick as 270 feet in some places. The character and depositional history of this unit are described in detail in Wickham, Johnson, and Glass (1988).

The Tiskilwa is a homogeneous, calcareous loam to clay loam till; when unoxidized it is brown to grayish brown with a pink cast. Although generally uniform, it has a weak to moderately strong blocky structure and may contain thin, discontinuous layers of gravel, sand, and silt. In many places the upper part of the Tiskilwa contains variably textured till interbedded with thin layers of sorted gravel, sand, silt, and clay. These sediments, thought to have been deposited at the margin or on top of the ablating (melting) glacier, are called ablation till. Ablation deposits are frequently coarser and less massive than underlying, more homogeneous till interpreted to have been deposited at or near the base of an active glacier.

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The Tiskilwa is a wedge-shaped deposit that thins and pinches out to the east (Wickham et al. 1988) and thickens toward the northwest to more than 150 feet below the Bloomington Morainic System and more than 270 feet below the Marengo Moraine. Toward the southeast, the Tiskilwa thins or is absent. This thinning may be attributed to either fluvial or glacial erosion (Wickham et al. 1988). East of the Fox River, the Tiskilwa may be found as bedrock valley fill; it also may be found in patches less than about 45 feet thick on highland surfaces buried by younger tills.

Sangamon Soil/Robein Silt These two units form a diagnostic stratigraphic marker that separates the Glasford and Wedron Formations. The top of the Sangamon and the Robein are usually within 5 feet of one another. Peat and wood fragments from the Robein are often incorporated into overlying till.

Glasford Formation As thick as 375 feet in the Troy Bedrock Valley west of the study area, (fig. 7), this unit lies above bedrock and below the Robein Silt, the Wedron Formation, or the Peoria Loess. The Banner Formation, stratigraphically below the Glasford, has not been identified in the area. The Glasford pinches out toward the east and has a patchy distribution east of the Fox River. The Glasford is apparently absent in the St. Charles Bedrock Valley, which is filled with till and outwash of the Tiskilwa Till Member of the Wedron Formation. The Aurora Bedrock Valley, a major tributary of the St. Charles, extends under the towns of Aurora and Montgomery, and the Fox River is filled with Glasford sediments. The valley fills of Illinoian and Wisconsinan age include significant sand and gravel deposits (Curry and Seaber 1990).

The stratigraphic units of the Glasford Formation are tentatively correlated with those in Boone and Winnebago Counties (Berg et al. 1985). Several of the till members, including the Herbert, Fairdale, Oregon, and Esmond Till Members, appear to be present in the area. In some places the basal Illinoian unit is the Kellerville Till Member (Kempton et al. 1987a,b).

Bedrock Units

The bedrock units beneath the overburden are composed of a thick sequence of Paleozoic sedimentary strata, predominantly dolomites, limestones, and dolomitic shales of Silurian and late Ordovician age. Stratigraphic subdivisions and principal lithologies are shown in figure 6, a stratigraphic column. The bedrock units generally dip toward the southeast at 10 to 15 feet per mile (0.1° to 0.2°).

Silurian Formations

Racine Formation This unit, as thick as 360 feet in places, is almost entirely pure reef rock in some places; in other places it is mostly silty or argillaceous, cherty, interreef rock. The Racine reef rock is exceptionally pure dolomite, largely vuggy to coarsely vuggy, medium grained, and light gray to white. Most of the interreef rock is impure, varying from moderately silty to very silty or very argillaceous and containing chert in irregularly scattered nodules. North and west of Chicago the formation thins and disappears; it increases in thickness toward the south and east.

Joliet Formation Two members of the Joliet present in northeastern Illinois are the Romeo and the Margraff. The *Romeo Member*, 18 to 34 feet thick, is a light gray to white, gray-weathering, pure, vuggy, thin- to medium-bedded dolomite, locally mottled with pink. The *Markgraf Member* consists of an upper zone, a fine-grained, dense dolomite containing a few thin shale partings and soft, porous chert nodules; a middle zone of argillaceous dolomite; and a lower silty zone in which closely spaced dolomitic shale laminae are found in the dolomite. The Markgraf is 9 to 51 feet thick.

Kankakee Formation Generally about 9 to 80 feet thick, the Kankakee has wavy beds of fine- to medium-grained, greenish gray, locally pinkish dolomite layers 1 to 3 inches thick. Beds are separated by thin laminae of pale green to light blue-green to greenish gray shale. Four zones of slightly different lithologies are difficult to identify in the subsurface.

Elwood Formation The Elwood is a cherty (containing nodules and layers up to 3 inches thick), slightly argillaceous, light gray, fine-grained dolomite. This unit is generally 20 to 30 feet thick where it has not been eroded.

Ordovician Groups and Formations
Maquoketa Group

Consisting of shales, dolomites and minor limestones, the Maquoketa is 0 to 210 feet thick in areas where overlying Silurian rocks have been removed, and 130 to 210 feet thick where covered by Silurian rocks. Pre-Silurian erosion on the surface of the Maquoketa may have partly controlled the thickness of the Maquoketa Group, producing channels that were subsequently filled by the Silurian Wilhelmi and Elwood Formations (Kolata and Graese 1983).

In the Chicago area, the Maquoketa Group shales and carbonates are subdivided into the following formations, listed in descending order: (1) the Neda Formation, a red, silty, hematitic shale containing flattened iron-oxide spheroids, is 0 to 15 feet thick; (2) the Brainard Shale, 1 to 136 feet thick, is a greenish gray, silty, fossiliferous, dolomitic, burrowed shale containing thin interbeds of dolomite; (3) the Fort Atkinson Dolomite, a light olive gray, crinoid-bryozoan-brachiopod dolomite, is commonly 15 to 40 feet thick; and (4) the Scales Shale, an olive gray, laminated, dolomitic shale, ranges from about 50 to 150 feet thick. These lithologies vary over short distances and have complex facies relationships (Graese and Kolata 1985).

Galena and Platteville Groups

These typically consist of pale yellow-brown, fine- to medium-grained, pure (95% carbonate, 5% or less clay and silt-sized quartz), fine- to medium-bedded dolomite, and one region of limestone. Beds are generally 6 to 12 inches thick, very wavy, and separated by thin (less than 1/16 inch), commonly stylolitic, green or brown shale laminae. In some places the carbonate rocks contain chert nodules. The combined thickness of the Galena and Platteville Groups generally ranges from 300 feet to more that 350 feet where overlain by the Maquoketa Group.

The Galena Group is subdivided into three formations in the area: the Wise Lake, Dunleith, and Guttenberg Formations. The thickness of the Galena Group ranges from 155 to 205 feet.

Wise Lake Formation This formation consists of pure, light brown, slightly vuggy dolomite. Generally thick bedded, the unit is separated by wavy, very thin, shaly laminae; within the area it is generally 140 feet thick. The upper 5 to 10 feet is often very vuggy and in some places is oil stained. In a few places in the Aurora area of Kane County, the Wise Lake is a very fine-grained to coarse-grained limestone. A widespread, thin, mixed-layer illite-smectite clay bed—the Dygerts K-Bentonite Bed (Willman and Kolata 1978)—less than 2 inches thick has been observed 80 to 100 feet below the top of the Wise Lake; the composition of the clay fraction is roughly 80 percent illite and 20 percent smectite.

Dunleith Formation This medium-grained, vuggy dolomite is approximately 45 feet thick. The upper 5 to 10 feet is commonly cherty; the remaining dolomite is similar but more vuggy than the overlying Wise Lake Formation.

Guttenberg Formation Pure dolomite separated by reddish brown shale laminae constitutes the Guttenberg. Within the area, it is about 2 feet thick; in many places it is absent.

Platteville Group

This group consists of several formations and members that are not readily distinguishable in the subsurface of northeastern Illinois. Overall, the Platteville consists of strata of gray to brown, very fine-grained, fossiliferous, pure to argillaceous dolomite, separated by thin brown and gray, wavy, shaly laminae. Locally, the dolomite grades into calcareous dolomite and very fine-grained limestone. The basal few feet are often sandy. Dark gray, mottled (burrowed) beds and chert nodules (less than 3 inches in diameter) may be present. The Platteville is 145 feet thick in the SSC study area.

Ancell Group

The Ancell comprises the Glenwood Formation and the underlying St. Peter Sandstone. The Glenwood, as thick as 75 feet in places, has a very variable lithology; it consists of a poorly sorted sandstone interbedded with shale and silty dolomite. The St. Peter Sandstone, generally ranging from 150 to 250 feet thick, is composed of white, fine- to medium-grained, friable sandstone.

Configuration and Nature of the Bedrock Surface

The top of the bedrock is a preglacial erosional surface that was further scoured during Pleistocene glaciation. Extensive drainage patterns eroded into this surface were subsequently covered by various glaciogenic materials. Recent erosion has cut into the surface of the glacial drift and in some places (in the Fox River, for instance) into the underlying rock units. Recent drainage channels are typically not associated with buried preglacial channels.

The top of the bedrock is moderately weathered and has a greater fracture frequency than does the underlying rock. The weathered zone, ranging in thickness from 0 to about 100 feet, is generally about 75 feet thick. In some areas the joints and fractures in the weathered zone have been widened and enlarged by solution; these enlarged fractures may yield water. Glaciers that moved across the area locally distorted, shoved, or incorporated the rocks and residual soils into the ice; in some places they completely removed the weathered debris, leaving a flat, often striated or grooved surface on relatively fresh bedrock. In other areas rubble or blocks are present at the bedrock surface (Johnson and Hansel 1986). In northeastern Illinois the bedrock surface can be seen only in quarries and in cores.

The Silurian rocks are most intensely jointed in the uppermost 50 to 75 feet. Horizontal and especially vertical joints at the Podschwit Quarry (fig. 9) are filled with clayey silt deposits up to 0.4 to 0.75 inches thick or have reddish brown to orange oxide stains. The stains indicate groundwater flow through fractures; the clayey silt deposits suggest downward translocation of fine-grained material facilitated by groundwater movement. The clay joint fillings are nearly pure illite, suggesting a low shrink-swell potential. At the Van Acker Pit, near-vertical crevices up to 1.5 feet across and 5 feet deep are found in the bedrock; they are filled with dark brown, silty clay (Robein Silt). The silty clay is composed of 50 percent smectite and 0.8 percent organic matter, suggesting a shrink-swell potential. This creviced zone on the bedrock surface, which was quarried and removed, originally covered about 40,000 square feet in a broad, shallow depression. A more significant portion of the bedrock surface at this site (covering 150,000 square feet) was flat and unweathered.

Ice-shove blocks of Silurian dolomite in the Avery and Boughton Quarries (fig. 9) are generally rectangular prisms measuring up to 10x10x15 feet. Most blocks appear to rest on the bedrock surface, but some lie on as much as 5 feet of drift. The drift is composed of matrix-supported bedrock rubble (Johnson and Hansel 1986).
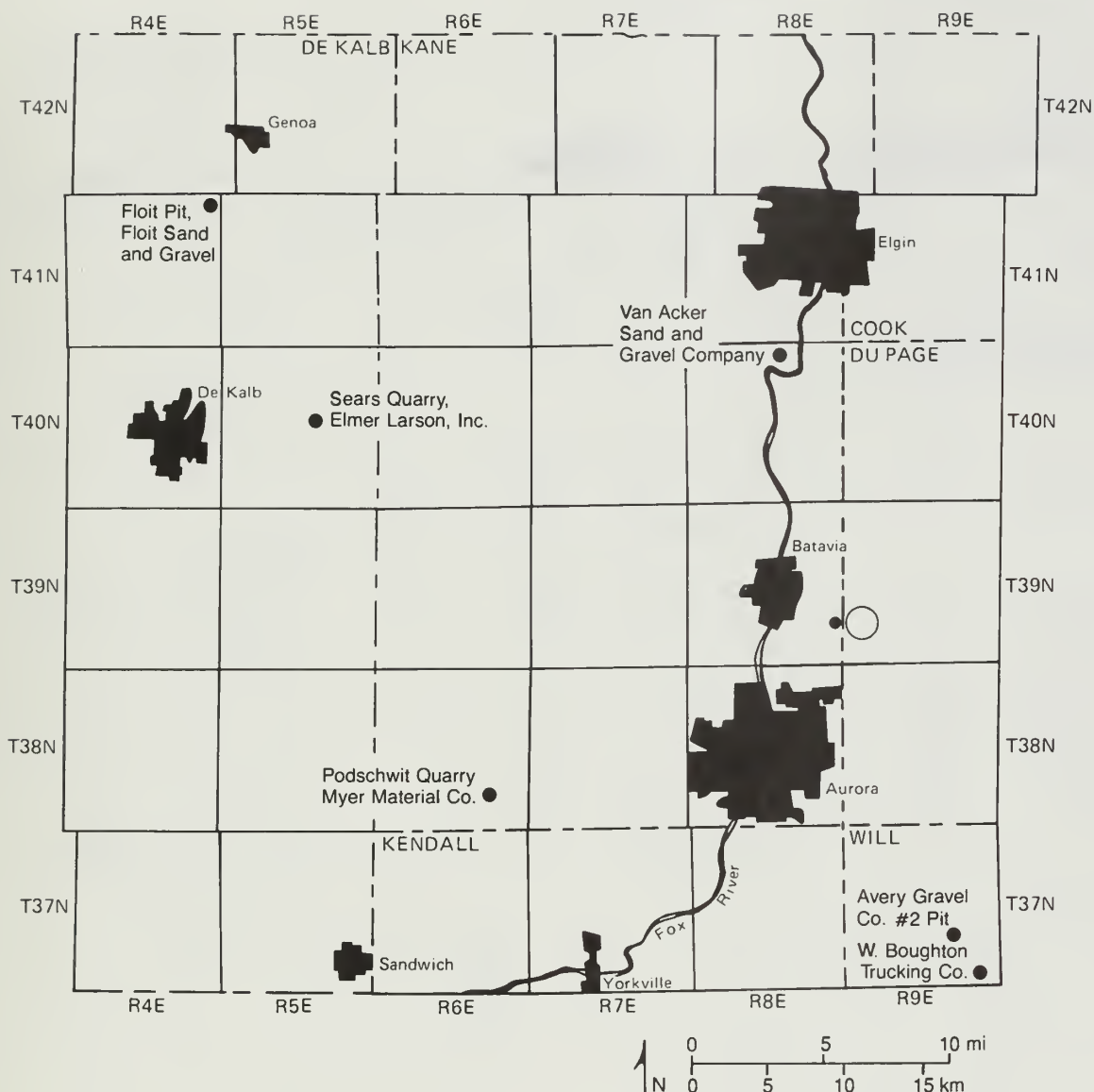
Figure 9 Locations of quarries and sand and gravel pits mentioned in the text.

The bedrock surface of the Maquoketa Group is variable because of the lithologic diversity of this unit. One exposure of the Maquoketa at and below the bedrock surface is at the Floit Pit (fig. 9), where interbeds of shale and argillaceous dolomite are relatively fresh and unweathered. However, some of the lowest RQD and core recovery values and highest fracture frequency values were encountered at or near the bedrock surface, where the top of rock was shale (table 2). Where the lithology is dolomite or limestone, the contact is generally sharp, and rock rubble is absent above the bedrock surface.

GEOLOGIC STRUCTURES

Bedding

The general dip of the bedrock units in the project area is to the southeast at a rate of about 10 feet per mile. An east-west cross section through all of northeastern Illinois (fig. 10) indicates that units are well stratified and that a wide range of bed thicknesses and unit spacings occur
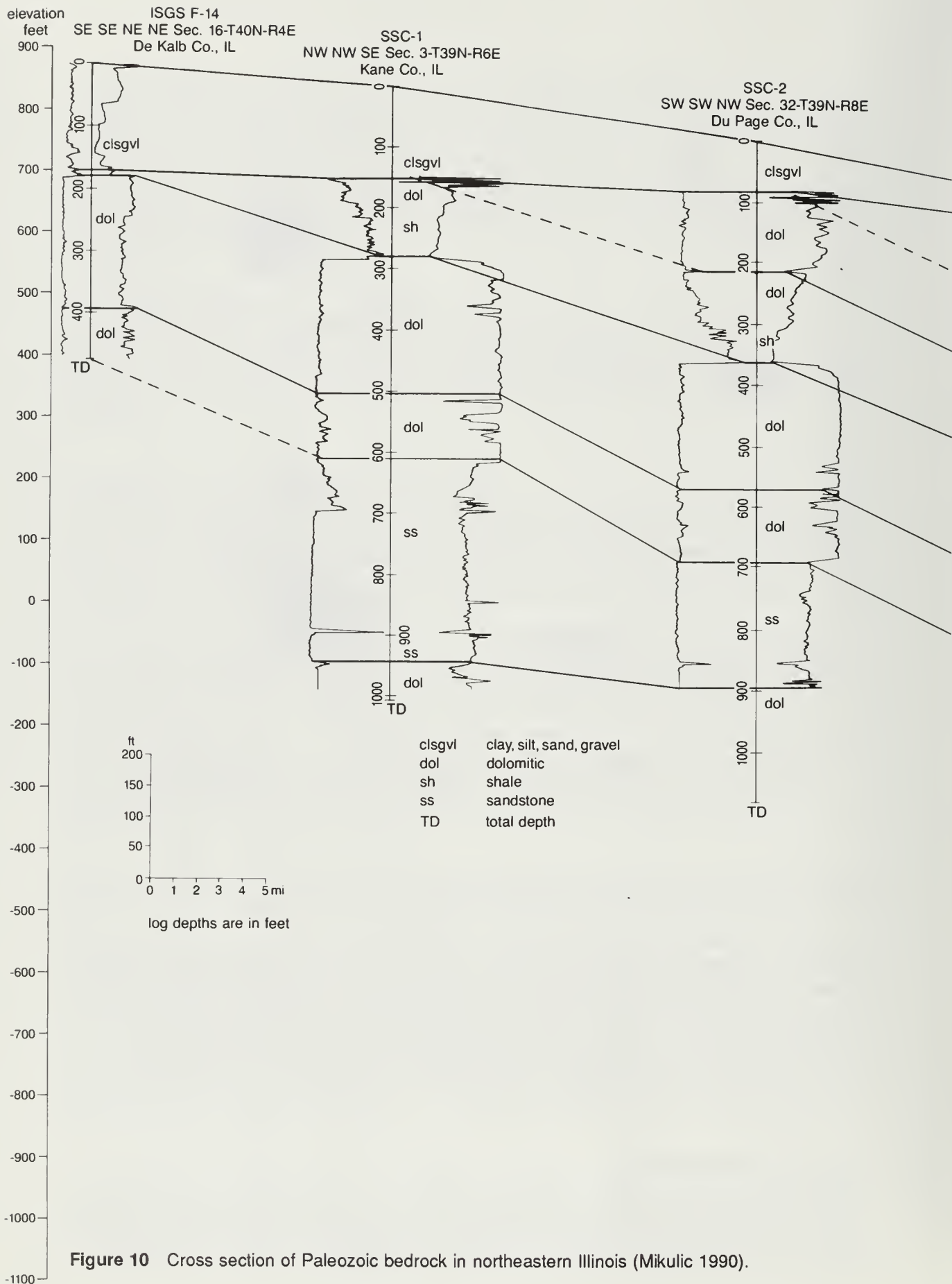
Figure 10 Cross section of Paleozoic bedrock in northeastern Illinois (Mikulic 1990).

clsgvl   clay, silt, sand, gravel
dol   dolomitic
sh   shale
ss   sandstone
TD   total depth

log depths are in feet
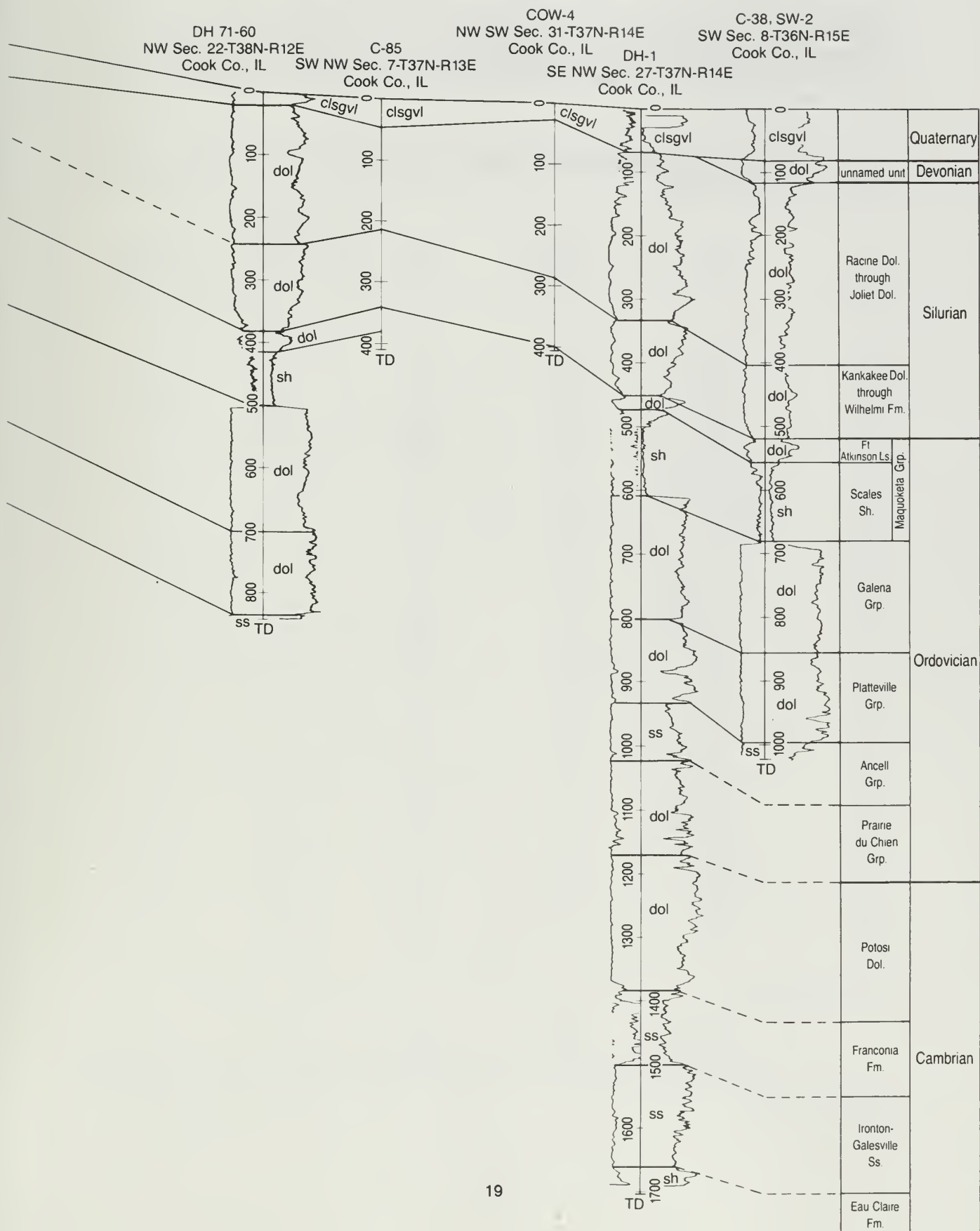
between significant bedding planes. These characteristics are observed at surface outcrops where weathering and stress relief increase or enhance bed parting frequency. The frequency of bedding planes observed in underground excavations is much less than at surface outcrops.

Most of the rock strata are conformable. Notable erosional contacts that give rise to local thickness variations can be observed at the base of the Silurian. Contacts between major rock units are commonly abrupt but may be gradational between dolomite, limestone, and shale within these major units.

Table 2 Summary of geotechnical conditions at or near the bedrock surface (results from first core runs in bedrock) in the SSC study area.

Borehole	Rock type	Core recovery (%)	RQD (%)	Depth below top of bedrock* for first core run (ft)	Fracture frequency (no./10 ft)
F-1	Silurian	85	70	3.3	5
F-2	Silurian	100	100	6.6	0
F-3	Maquoketa	96	96	6.1	4
F-4	Silurian	100	100	7.3	3
F-5	Maquoketa	100	84	2.5	2
F-6	Silurian	100	100	3.0	6
F-7	Silurian	100	100	3.5	0
F-8	Maquoketa	94	93	12.3	2
F-9	Maquoketa	99	91	8.9	5
F-10	Silurian	100	100	5.0	1
F-11	Galena	100	98	0.7	8
F-12	Maquoketa	70	70	14.1	0
F-13	Maquoketa	56	24	0.0	2
F-14	Maquoketa	100	100	1.0	3
F-15	Maquoketa	100	100	0.0	4
F-16	Maquoketa	100	100	0.0	0
F-17	Galena	100	88	0.0	6
S-18	Silurian	100	100	3.0	3
S-19	Maquoketa	96	94	1.3	4
S-20	Silurian	100	100	1.4	0
S-21	Maquoketa	85	80	8.0	1
S-22	Silurian	90	0	0.0	0
S-23	Maquoketa	99	99	0.0	5
S-24	Maquoketa	85	85	0.4	1
S-24A	Maquoketa	100	100	0.0	0
S-25	Silurian	92	84	15.0	7
S-26	Maquoketa	100	91	4.2	0
S-27	Silurian	99	94	0.8	5
S-28	Silurian	100	100	1.5	0
S-29	Silurian	74	74	11.3	1
S-30	Silurian	100	100	4.5	0
Averages per rock type					
	Silurian	96	87	4.7	2
	Maquoketa	92	87	3.9	2
	Galena	100	93	0.4	7

*Top of first core run.

Joints

Two dominant systematic joint sets, one striking approximately northeast and the other northwest, have been identified in northeastern Illinois. Foote (1982) mapped joint directions in quarries in northeastern Illinois (fig. 11). Joint directions in Kane and western Du Page Counties were observed in angled boreholes F-8, S-25, and S-29 (fig. 12). Joints of both sets are steeply dipping to vertical (see table 3, a summary of joint dips logged in all SSC exploration holes except F-8, F-13, S-25, and S-29). The vertical holes provide an underestimate of vertical joint occurrence.

Additional data on orientation, dip, spacing, and other joint characteristics were obtained from observations made during the construction of TARP, and from SSC exploration holes. A
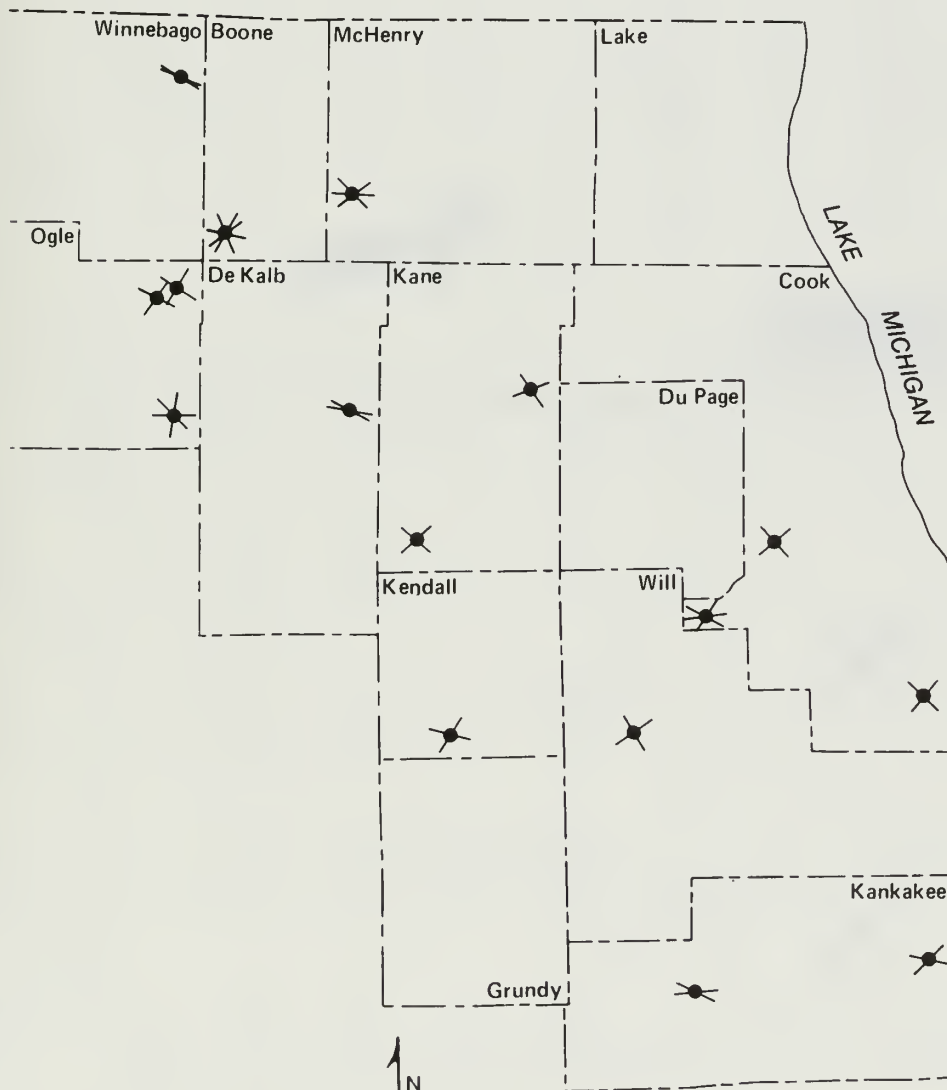
Figure 11 Location and strike of joints measured by Foote (1982) in surface quarries.

summary of joint orientations is provided in table 1 and a summary of joint characteristics in SSC exploratory boreholes in table 4. In most TARP tunnels, the spacing of persistent joints ranged from several tens to hundreds of feet (table 1).

On the basis of observations of outcrops and rock core data in the SSC study area, joints appear to be more open (filled or not filled) near the bedrock surface and are locally stained to depths of 100 feet. Most of the near-surface joints have widths or apertures ranging from hairline cracks to a fraction of an inch. A few joints display greater widths or aperatures, particularly those close to the bedrock surface, where solution-widening has occurred. In the subsurface, a few joints are filled with gray, black, or green shaly material or clay. Mineral infillings of calcite and pyrite occur in up to 13 to 28 percent of the joints in dolomite. Pressure solution activity has resulted in the formation of stylolites on joints as well as on bedding surfaces.
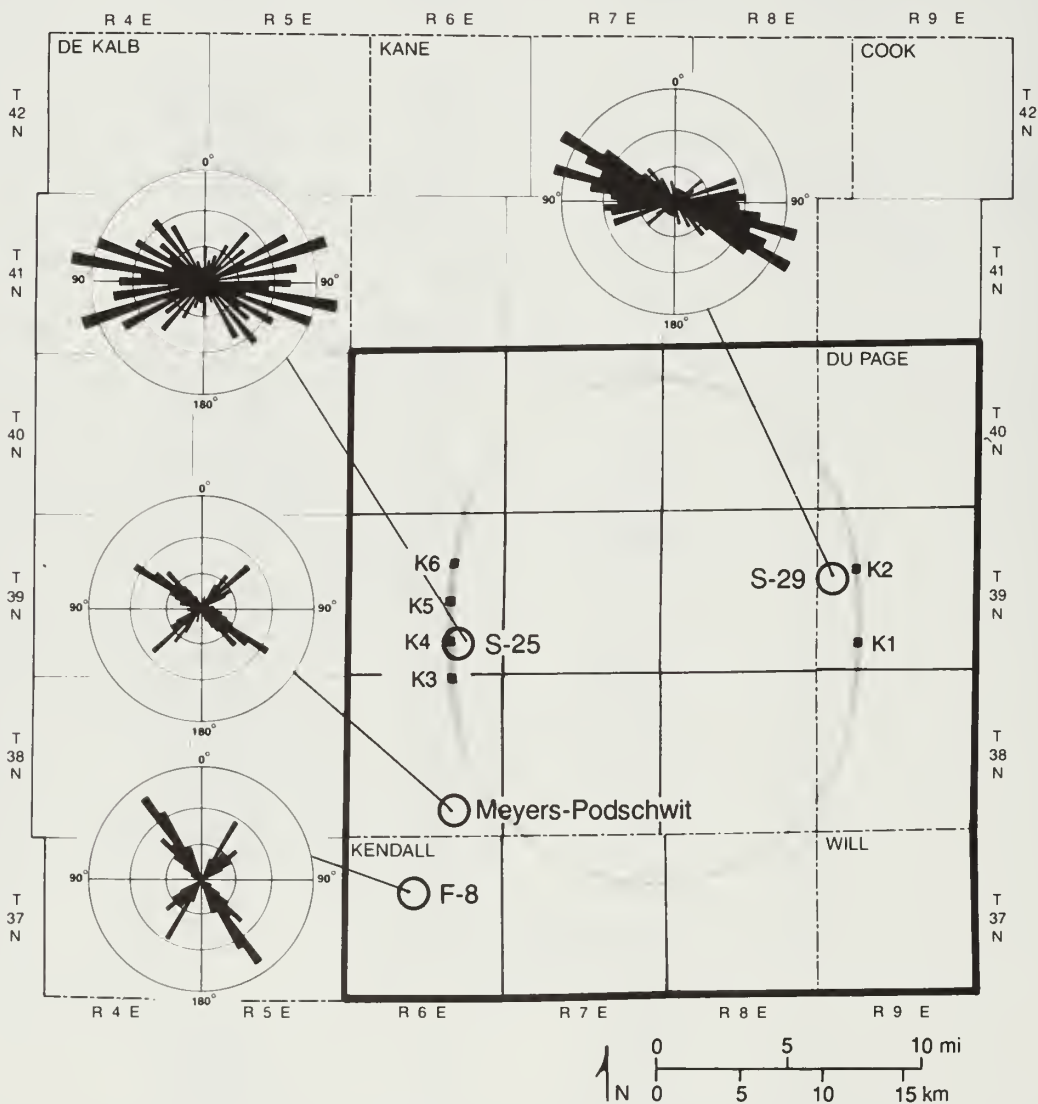
Figure 12 Joint strike directions as measured in angle boreholes and in the Myers-Podschwit quarry.

Table 3 Number of joints (per formation) per dip degrees.

Dip degree	Silurian No.	Silurian %	Maquoketa No.	Maquoketa %	Wise Lake No.	Wise Lake %	Dunleith No.	Dunleith %	Platteville No.	Platteville %
90	53	56.4	116	40.0	179	48.2	46	45.5	142	49.8
85	5	5.3	22	7.6	53	14.3	7	6.9	42	14.7
80	6	6.4	25	8.6	40	10.8	10	9.9	30	10.5
75	4	4.3	17	5.9	17	4.6	12	11.9	18	6.3
70	3	3.2	12	4.1	21	5.7	5	5.0	12	4.2
65	4	4.3	9	3.1	3	0.8	3	3.0	4	1.4
60	3	3.2	15	5.2	12	3.2	3	3.0	4	1.4
55	0	0.0	5	1.7	1	0.3	0	0.0	7	2.5
50	0	0.0	13	4.5	14	3.8	3	3.0	4	1.4
45	0	0.0	4	1.4	2	0.5	0	0.0	4	1.4
40	0	0.0	6	2.1	2	0.5	0	0.0	7	2.5
35	0	0.0	3	1.0	0	0.0	0	0.0	1	0.4
30	1	1.1	5	1.7	1	0.3	0	0.0	1	0.4
25	1	1.1	4	1.4	0	0.0	1	1.0	0	0.0
20	0	0.0	8	2.8	0	0.0	0	0.0	1	1.4
15	0	0.0	5	1.7	0	0.0	0	0.0	1	0.4
10	1	1.1	7	2.4	4	1.1	0	0.0	1	0.4
5	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
0	13	13.8	14	4.8	22	5.9	11	10.9	6	2.1
Total	94		290		371		101		285	

Table 4 Summary of joint characteristics per stratigraphic unit in SSC exploratory boreholes.

	Silurian No.	Silurian %	Maquoketa No.	Maquoketa %	Wise Lake No.	Wise Lake %	Dunleith No.	Dunleith %	Platteville No.	Platteville %
Filling										
none	75	44	223	59	414	69	117	74	228	70
partial	64	37	88	23	123	20	25	16	65	20
complete	33	19	68	18	67	11	17	11	31	10
Type of filling*										
shale	3	2	2	1	22	4	3	2	5	2
clay	67	39	48	13	67	11	11	7	49	15
mineral	31	18	111	29	104	17	29	18	42	13
healed	26	15	111	29	131	22	39	25	80	25
Condition										
sound	154	90	367	97	571	95	139	87	316	97
altered	18	10	12	3	33	5	20	13	10	3
very alt.	0	0	0	0	0	0	0	0	0	0
Roughness										
uneven	67	39	187	49	186	31	46	29	90	28
wavy	85	49	179	47	379	63	95	60	206	63
planar	20	12	13	3	39	6	18	11	30	9
Asperite										
rough	77	48	159	43	360	60	72	46	144	43
smooth	76	48	200	54	239	40	81	52	174	52
slickensided	7	4	11	3	3	0	2	1	14	4

* percent of all joint faces

Diagenetic Structures

Diagenetic deformation features, consisting of randomly oriented slickensides, were noted in the lower, shaley section of the Maquoketa in three SSC exploratory boreholes (F-1, F-2, and F-4). The extent of these zones is not well known; it seems likely that the deformation features occur only locally, because three additional nearby boreholes (S-28, S-29, and SSC-2) did not encounter them. The features are interpreted as nontectonic in origin, probably the product of diagenesis and sediment consolidation.

Faults

There are no known active faults in northeastern Illinois. The largest fault in the general area is the Sandwich Fault Zone, which extends northwesterly from near Manhattan in Will County to near Oregon in Ogle County—a distance of 85 miles (Kolata et al. 1978). In investigations for TARP and the proposed SSC, several different seismic techniques were used to detect offsets in the bedrock strata. More than 100 miles of seismic refraction and reflection surveys were performed for the SSC exploration in Kane and western Du Page Counties. Only two possible minor offsets of up to 13 feet were found in the top of the Galena dolomite. Seismic exploration for TARP produced 420 miles of seismic lines that traversed the Chicago area. The data suggested that several faults of displacements of 10 to 50 feet were present on the top of the Galena Group (Buschbach and Heim 1972). Later tunneling through the area confirmed some of the faults, but others were not found.

Table 5 Seismic risk assigned to northeastern Illinois by various seismic risk maps.

Reference	Seismic zone or peak ground acceleration (% of gravity)	Definition
Algermissen (1969)	1	Minor damage; distant earthquakes may cause damage to structures with fundamental periods greater than 1.0 seconds; corresponds to Intensity V and VI of the Modified Mercalli Scale
Uniform Building Code (1976, 1982)	1	Ditto (based on Algermissen 1969)
Algermissen and Perkins (1976)	less than 4%	90% probability of nonexceedance in 50-year period
Applied Technology Council (ATC-3-06, 1978)	less than 5%	Ditto
Algermissen and others Open File Report 82-1033, pl. 2 (1982)	less than 4%	90% probability of nonexceedance in 50-year period
U.S. Army Corps of Engineers ER110-2-1806 (1983)	1	Minor damage; seismic coefficient 0.05
Proposed revised SEAOC Seismic Zone Map (1985)	0	Less than 0.05 effective peak acceleration; 90% probability of non-exceedance in 50-year period

Table 6 Average hydraulic conductivities of units.

Stratigraphic unit	Hydrogeologic unit	Range of K (cm/sec)
Drift	Outwash sands and gravels	1×10^{-2} to 1×10^{-4}
	Glacial tills	1×10^{-6} to 1×10^{-8}
Silurian	Upper bedrock aquifer	1×10^{-2} to 1×10^{-4}
Maquoketa	Upper bedrock aquifer	1×10^{-4} to 1×10^{-6}
Maquoketa	Upper Ordovician aquitard	1×10^{-5} to 1×10^{-6}
Galena-Platteville	Upper Ordovician aquitard	1×10^{-5} to 1×10^{-6}
Ancell	Midwest sandstone aqiufer	3×10^{-3}

SEISMICITY

The proposed SSC site in northeastern Illinois was located within a zone of the central mid-continent that is tectonically stable and seismically quiescent—Zone 1 of Algermissen (1969) and the Uniform Building Code (1982). The seismic hazard posed to structures in this region is estimated to be very low, because the closest known earthquake source zones capable of producing ground motions of any significance to engineering design or operational requirements are located several hundred miles to the south. These include the New Madrid Seismic Zone and related geologic structures of the Mississippi valley and the Wabash Valley Fault System. Heigold and Larsen (1990) published a compilation of earthquake events epicentered in Illinois.

No known active faults exist in northeastern Illinois. The undisturbed Pleistocene sediments across the Sandwich Fault in bedrock (Kolata et al. 1978) indicate that the latest movement on the Sandwich Fault Zone—the closest zone of significant faulting—must have occurred more than 200,000 years ago. Various national seismic zonation studies conclude that northeastern Illinois is in one of the lowest seismic risk categories (table 5), with probable peak ground acceleration estimates less than 0.05 g (90% probability of not being exceeded in a 50-year period).

In general, the sand and gravel and clayey lacustrine materials in the area are not liquefiable during a seismic event according to the material properties and standards presented by Seed and Idriss (1982).

HYDROGEOLOGIC CONDITIONS

Hydrogeologic Units

Groundwater conditions in the area are partly related to the characteristics of geological materials. Geologic materials of similar characteristics and settings can produce distinct layers of groundwater or hydrogeologic units. The average hydraulic conductivities of each of these units are given in table 6; detailed information is presented in each of the SSC drilling reports included in Kempton et al. (1987a,b) and Curry et al. (1988).

Drift Aquifers These units are locally occurring, permeable, sand and gravel layers or lenses, primarily outwash deposits, separated by relatively impermeable clayey and silty units (aquicludes and aquitards) consisting mostly of till and lacustrine deposits. Although the drift is saturated below the water table (the top of the zone of saturation), only permeable materials that yield a significant quantity of groundwater are considered aquifers. Drift aquifers can be categorized broadly as surficial, buried, and basal. Buried aquifers are isolated or partly interconnected lenses or layers of sand and gravel. Basal aquifers, commonly under artesian

conditions, are generally discontinuous layers of sand and gravel resting on the bedrock; they may interact with groundwater in the upper bedrock aquifer. Infiltration of water from the basal drift aquifer into the upper bedrock aquifer may be enhanced by thick basal deposits of sand and gravel, and the basal drift aquifers and the upper bedrock aquifer may operate together as a single hydrologic unit, irrespective of geologic formation or lithology.

The hydrogeology of the glacial drift is variable because of the heterogeneous characteristic of the materials. Thus, groundwater occurrence, heads, and yields are dependent on local site conditions.

Upper Bedrock Aquifer   This unit is the upper 50 to 75 feet of weathered and fractured bedrock (stress-relieved), irrespective of stratigraphy or lithology but dominantly in carbonate units (Silurian dolomite in particular); it has a low primary permeability and a relatively high secondary permeability. The hydrologic regime of the upper bedrock aquifer resembles that of an aquifer overlying a relatively impermeable unit. The upper bedrock aquifer consists of local flow systems, mostly associated with fractures, irrespective of geologic formation or lithology.

Upper Ordovician Aquitard   This unit of relatively low primary and secondary permeability) is in the Maquoketa shale and dolomite and the Galena and Platteville dolomites and limestones. These rock units act as a base to the upper bedrock aquifer and a confining unit to the underlying aquifer. Groundwater in the upper bedrock aquifer is confined near the bedrock surface.

Groundwater in the aquitard occurs mostly in secondary openings such as open joints or bedding planes. Observations during the SSC exploratory drilling program indicated that open fractures occurred less frequently with depth.

Deep Bedrock Aquifers (Midwest Sandstone Aquifer System)   This is a relatively high-permeability artesian aquifer system below the Galena and Platteville. It includes sandstone units of the Ancell Group (Glenwood and St. Peter Formations), deeper formations (such as the Ironton-Galesville), and the basal Mt. Simon Sandstone.

Results of a pump test (Vaiden et al. 1988) performed in SSC-1 within the Ancell Group sandstone of the deep bedrock aquifer system indicate very little hydraulic connection between the sandstone and the overlying Galena and Platteville Groups.

Groundwater Levels

The potentiometric surface in the upper bedrock aquifer is generally at or just above the bedrock surface. The surfaces of piezometers in wells open only to the upper bedrock aquifer are higher than those finished in the underlying aquitard or deep bedrock aquifer. In areas where sand and gravel deposits immediately overlie the bedrock surface, groundwater levels are likely to be the same as those in the upper bedrock aquifer.

The regional potentiometric surface of the Midwest sandstone aquifer system was delineated on the basis of data from deep wells in the Ancell Group and Ironton-Galesville Sandstones. The potentiometric surface for this aquifer is as high as the Galena and Platteville Groups. The potentiometric surface in the Galena and Platteville closely parallels the regional potentiometric surface of the Midwest sandstone aquifer system, even in areas where the surface has been lowered by pumping, as in the Fox River region. This suggests groundwater in the Galena and Platteville is approaching equilibrium with water levels in the midwest sandstone aquifer system.

Groundwater Inflow

Evaluations of the results of SSC site-specific hydrogeologic studies and previous underground construction experience with TARP indicate that groundwater inflow will be unlikely to adversely affect the construction of future tunnels and chambers in this area. The likelihood that very large, uncontrollable inflows would be encountered during construction is considered exceedingly remote. Hydraulic conductivities in bedrock units forming a nonaquifer system (i.e., the Maquoketa, Galena, and Platteville of the upper Ordovician aquitard, as determined by in situ permeability testing, range from 1×10^{-5} to less than 1×10^{-6} cm/sec. In the Maquoketa parts of the upper bedrock aquifer the hydraulic conductivities range from 1×10^{-4} to less than 1×10^{-6} cm/sec—values that characterize moderate- to low-permeablility rock. As previously noted, there are no known major zones of faulted or severely sheared rock that could be water-bearing. Joints at the depth are mostly tight, healed, or filled with impermeable (clay-shale) material. Solution-widened joints occur only in dolomite in the weathered upper bedrock zone. Vugginess, noted in the drilling of some units, does not contribute to any substantial sustained flow, since the vugs do not form an interconnected system. The low groundwater yield of the Maquoketa, Galena, and Platteville units is demonstrated by the fact that water supply wells are finished either in the upper bedrock aquifer (mainly in the Silurian), or below in the midwest sandstone aquifer system.

TARP construction experiences, discussed earlier in this report, have confirmed that groundwater inflow should not be a significant problem. During construction of seven TARP Mainstream tunnels, totaling nearly 21 miles of TBM-bored length (almost 20 miles of tunnel greater than 32 feet in diameter), the inflow from joints, bedding, and other bedrock features averaged only 112 gpm/mile before grouting (Harza 1984). Grouting and placement of concrete lining reduced this average inflow to less than 52 gpm/mile (the design expectation). Inflows into the TARP North and South Pump Houses (each 310 feet long, 63 feet wide, and 96 feet high) totaled only 16 and 30 gpm initially despite more than 200 feet of head in surrounding saturated rock. These flows decreased over time (Harza 1983).

GEOTECHNICAL CHARACTERISTICS OF GLACIAL MATERIALS

General Engineering Properties of Overburden Types

As mentioned earlier, the overburden materials in the area consist predominantly of glacial till, glacial outwash, and lacustrine deposits; minor amounts of loess and organic-rich sediment (generally less than 5% organic carbon, rarely wood or peat) also occur. Table 7 summaries the engineering properties of these five general material types, which are discussed briefly in this section.

Loess consists of wind-deposited silt and finer sized particles composed of quartz and clay derived from large quantities of outwash. The clay mineralogy of the clay-size fraction in the loess changes with the source of the original loess deposit—expandable minerals such as mont- morillonite attributed to the Mississippi Valley source, or a high content of illite attributed to the Lake Michigan lobes. Loess is susceptible to erosion and piping; it has a soft consistency when wet and a medium to stiff consistency when dry. Most of the modern soils in Illinois are developed in loess. The Unified Soil Classification System (USCS) designation for loess is CL, ML, or MH with an average Liquid Limit of 41.4 percent and a Plasticity Index of 21.6 percent. Its estimated average unconfined compressive strength obtained from pocket penetrometer (Qp) readings is 1.5 tons per square foot.

Table 7 Summary of geotechnical properties of general types of overburden materials in the study area.

Material	SPT (N) Blow counts (ft)	Qp[##] (pocket penetrometer)	W (moisture content %)	Dry density (gm/cm^3)[*]	Moist density (gm/cm^3)	Liquid limit	Plasticity index
Loess	11.4 ±6.8[#] 6% ≥4.5 (49)	1.5 ±0.9 0% refusal (31)	1.51 ±0.08 (38)	2.13 ±0.2 (4)	41.4 (3)	21.6 (40)	2.5±8.8 (40)
Till	33.0 ±22.0 14% refusal (846)	2.3 ±1.0 27% ≥4.5 (512)	12.4 ±3.3 (745)	2.20 ±0.17 (91)	2.40 ±0.18 (145)	29.9 (336)	14.1 (336)
Peat	1.9 0% refusal (20)	0.3 (10)	111.8 (20)	0.83 (5)	-- 	-- 	--
Lacustrine	38.1 ±25.4 17% refusal (137)	2.1 ±1.2 7% ≥4.5 (61)	18.0 ±4.8 (77)	2.00 ±0.27 (7)	2.36 ±0.19 (10)	-- 	--
Outwash	43.9 ±21.9 17% refusal (259)	1.5 (4)	17.0 (19)	-- 	-- 	-- 	--
Buried organic-rich sediment	49.8 ±31.7 55% refusal (9)	2.4 ±1.4 57% ≥4.5 (6)	28.9 ±26.7 (15)	-- 	-- 	-- 	--

Material	% gravel (% of whole sample)	<2mm fraction % sand 2-0.62mm	<2mm fraction % silt 0.62-0.0039mm	<2mm fraction % clay <0.0039mm	USCS classification
Loess	2.5 ±8.8 (39)	13.4 ±12.9 (39)	55.0 ±11.0 (39)	31.6 ±12.6 (39)	CL,MH,ML
Till	8.4 ±7.9 (884)	31.3 ±13.1 (884)	40.2 ±8.1 (884)	28.5 ±11.2 (884)	CL
Peat	2.0 (6)	8.0 (10)	52.4 (10)	39.6 (10)	OH,OL
Lacustrine	2.5 ±6.6 (106)	21.1 ±24.2 (106)	56.6 ±3 (106)	22.2 ±17.7 (106)	CL,ML,SM
Outwash	28.5 (113)	52.7 (113)	32.5 (113)	14.8 (113)	GW,SW,SP
Buried organic-rich sediment	4.8 ±10.3 (14)	25.5 ±18.8 (14)	43.7 ±13.4 (14)	30.8 ±18.1 (14)	OH,OL

[#] values are the mean ± standard deviation
[##] unconfined compressive strength in tons per square feet
( ) total number of samples
[*] grams per cubic centimeter
Sources: Kempton et al. 1985, 1987a,b

Till consists of overconsolidated, well graded (very poorly sorted) clay, silt, sand, and larger particles such as pebbles or cobbles; it is used extensively as foundation material, since it has a stiff to very stiff consistency and low compressibility. The upper till at a site may be weathered (oxidized) and jointed; these characteristics generally affect water movement but not necessarily strength (Kemmis 1978). The USCS designation is CL, and the tills have an average Liquid Limit of 29.9 percent and a Plasticity Index of 14.1 percent. Its estimated average unconfined compressive strength from pocket penetrometer readings is 2.3 tons per square foot.

Lacustrine material overlain by till has characteristics similar to those of till: it is overconsolidated, is medium to very stiff, and has low permeability. It may be organic-rich (up to 5%) and soft. The USCS designation for this material is CL, ML, or SM; it has an average Qp of 2.1 tons per square foot.

Outwash, mostly sand and gravel, generally contains less than 15 percent silt and finer particles and is well graded. Most outwash (buried or surficial) is medium to very dense and is a suitable foundation material. The USCS designation is GW, SW, or SP; the average Qp is 1.5 tons per square foot; this value is probably misleading, because the average blow counts per foot value (Standard Penetration Test) is 44. The Qp is not performed on gravel or stony matrices.

Organic sediment also occurs at the surface in small areas, generally in bogs (Grayslake Peat) or in the subsurface (Robein Silt). The Grayslake Peat, which may consist entirely of organic matter, has a medium to stiff consistency. Its moisture content may be as high as 700 percent; it is therefore undesirable as foundation material because it is highly compressible. Peat occurring at the surface is removed prior to foundation construction. The USCS designation is is OH or OL; it has an average Qp of 2.4 tons per square foot, and an average blow count value of 50 per foot.

General Engineering Properties of Selected Drift Units

The geotechnical properties of specific drift units are summarized in table 8 and described briefly in the following paragraphs.

Richland or Peoria Loess These units have a soft consistency when saturated but a medium to stiff consistency when dry (Bergstrom et al. 1976). The clay-mineral fraction of the loess contains about 75-percent expandable clay minerals, indicating moderate shrink-swell potential. The Richland and Peoria are generally less than 5 feet thick; they have a Qp of about 2 and a range of <1 to 4 tons per square foot.

Equality Formation The Equality is normally consolidated, and this is reflected in its mean engineering properties—moisture content, 29 percent; blow counts, 20; and unconfined compressive strength, 1 ton per square foot—which indicate a medium to stiff material. Moisture content, when compared to the Liquid Limit and Plastic Limit, indicates normal or overconsolidated conditions. Organic content may increase from the bottom to the top of a thick sequence of the Equality, which accounts for the widely variable moisture content and blow counts for this formation.

Wedron Formation

Yorkville Till Member The Yorkville particle-size distribution is 10-46-44; (sand-silt-clay, respectively) with a mean moisture content of 16.5 percent. In addition, N values show little variability (mean, 28 blows/foot). The average moisture content of the Yorkville is higher than that of the Tiskilwa, chiefly because of its higher silt and clay content, and perhaps also

because of its lower density. Unconfined compressive strength (Qp) of the Yorkville varies widely with a range from soft to hard consistency.

Malden Till Member The Malden can be categorized into two regional types in the study area (Landon and Kempton 1971). One type, present east of and along the Fox River, is found beneath the Fermilab Accelerator site where the Malden occurs beneath Yorkville deposits. Here the till has a stiff to very stiff consistency but is associated with sand and gravel layers up to 15 feet thick as well as with stratified silt, fine sand, and clay beds (Unit C and D in Landon and Kempton 1971). The other regional type occurs at or near the surface in the Elburn Complex; here the Malden is a surficial deposit and the till is associated with abundant, poorly sorted sediments and deposits of dense sand and gravel up to 70 feet thick.

Tiskilwa Till Member The particle-size distribution for what is interpreted as Tiskilwa basal till is 35-38-27 (sand-silt-clay), and the mean moisture content is 10.6 percent. Unconfined compressive strength (Qp) and blow count (N) data vary more than do texture and moisture content. The mean blow count is 45; values greater than 100 probably represent encounters with boulders, cobbles or smaller pebble-sized clasts that blocked the split spoon penetration; eliminating these values, the mean blow count is 35. Unconfined compressive strength commonly exceeds 4.5 tons per square foot.

Robein Silt-Sangamon Soil The organic matter content of these deposits is generally 1 percent or less, but the Robein contains up to about 16-percent organic matter, which would make it compressible. Organic-rich layers are usually removed from construction sites so that structures can rest on less compressible material. The clay fraction of the Robein may also contain about 60 percent expandable clay minerals, indicating some shrink-swell potential.

Glasford Formation (Undifferentiated) This till, which may include stratified gravel, sand, and silt, has a grain size distribution of 38-36-26 (sand-silt-clay). It has a high density (averaging 144 pounds per cubic foot) and a hard consistency (Qp averaging 4 tons per square foot) and average blow counts of 57, with a range from 22 to 106.

GEOTECHNICAL CHARACTERISTICS OF ROCK UNITS

The rock types in northeastern Illinois exhibit a range of engineering characteristics. Dolomites and limestones are relatively homogeneous and strong and constitute excellent foundation material. Some shale units, however, are not as strong because of their mineralogy and weathering characteristics, laminated structure, joint characteristics, and hetergeneity. Some dolomite at the top of the bedrock exhibits weathered features, solutioned joints, and separation along horizontal laminae. Nevertheless, the dolomites and even the shales are good foundation and tunneling materials.

The TARP project produced a large database of strength-test values. These values are presented in Harza (1975b), summarized in table 9, and presented in a condensed version in appendix A. Many of the tests were made on the Silurian formations, in which most of the TARP tunnels were excavated. Results from tests on the Ordovician-age Galena and Platteville Groups are also given in appendix A.

A comprehensive testing program was undertaken to study the properties of the different types of rocks occurring in the proposed SSC site area. Part of the program was designed to evaluate the use of tunnel boring machines (TBMs) for tunnel excavation. Results of the rock tests are summarized in table 10, and individual test results are given in appendix B.

Table 8 Geotechnical properties and particle-size distribution of specific drift units in the SSC study area.

Unit	Standard Penetration Test (N) (blows/ft)	Compressive strength (Q_p) (TSF)	Moisture content (W) (%)	Dry density (dd) (lbs/ft³)	Gravel (% of whole sample)	Particle-size determination <2mm fraction Sand (%)	Silt (%)	Clay (%)
Cahokia Alluvium	$\overline{X}$ 8	1	26	107	6	29	45	26
	n 25	15	23	7	44	48	48	48
	R** 2-25	0-3	11-51	100-117	0-51	0-59	16-7	36-49
Grayslake Peat	$\overline{X}$ 2	<1	112	52	2	8	52	40
	n 20	10	20	5	6	10	10	10
	R 0-5	<1	34-265	30-74	0-30-23	26-72	22-61	
Richland Loess	$\overline{X}$ 12	2	24	101	1	7	50	43
	n 6	10	10	5	8	8	8	8
	R 9-19	<1-4	20-31	94-104	0-3	0-15	40-61	35-53
Equality Formation	$\overline{X}$ 20	1	29	96	1	8	60	32
	n 70	133	145	65	172	198	198	198
	R 3-68	<1-4	11-145	43-131	0-10	0-30	9-94	2-84
Henry Formation	$\overline{X}$ 22	2	17	-	29	53	32	15
	n 251	4	19	-	112	113	113	113
	R 3-119	<1-2	11-23	-	0-76	5-91	2-92	0-53
Wadsworth Till Member	$\overline{X}$ 24	2	17	-	6	14	43	43
	n 55	39	43	-	54	54	54	54
	R -	-	-	-	-	-	-	-
Haeger Till Member	$\overline{X}$ 36	2	12	-	21	38	49	13
	n 19	7	10	-	27	27	27	27
	R -	-	-	-	5-41	16-53	39-65	5-24
Yorkville Till Member (ablation facies)	$\overline{X}$ 20	3	13	126	12	26	42	32
	n 29	48	55	25	80	80	80	80
	R 11-26	<1-8	10-24	114-136	2-40	7-53	17-66	15-90
Yorkville Till Member (till facies)	$\overline{X}$ 28	4	17	117	4	10	46	44
	n 569	927	1,469	608	379	987	987	987
	R 3-106	<1-10	6-35	92-138	0-29	0-54	18-83	13-68
Malden Till Member	$\overline{X}$ 17	2	13	128	13	36	43	21
	n 33	37	44	13	54	54	54	54
	R 5-100	<1-4	9-25	119-135	0-32	4-57	23-63	6-38
Malden Till Member (outwash facies)	$\overline{X}$ 32	-	11	1-4	5	55	34	11
	n 44	-	3	1	13	13	13	13
	R 6-100	-	8-13	-	0-23	3-83	4-80	0-29
Tiskilwa Till Member (ablation facies)	$\overline{X}$ 28	2	10	-	17	43	39	18
	n 132	12	105	-	41	43	43	43
	R 6-77	1-6	6-30	-	5-70	16-62	18-54	8-37
Tiskilwa Till Member (till facies)	$\overline{X}$ 35	3	11	124	7	35	38	27
	n 533	370	364	84	315	315	315	315
	R 3-600	<1-11	8-16	83-156	0-25	4-52	28-71	6-45
Robein Silt/ Sangamon Soil	$\overline{X}$ 258	4	17	98	8	36	32	32
	n 7	8	7	1	3	3	3	3
	R 152-440	3-4	12-23	98	<1-16	30-44	26-38	17-40
Glasford Formation undivided	$\overline{X}$ 57	4	11	144*	11	38	36	26
	n 58	49	59	8	71	77	77	77
	R 22-106	1-5	6-18	124-150	,1-57	10-58	23-56	11-50

$\overline{X}$ = mean; R = range; n = number of samples; * = moist density
Sources: Landon and Kempton 1971, Schmitt 1985, Kempton et al. 1987a,b, and data on open file at the ISGS.

Table 9 Summary of average TARP geotechnical data.

Rock type	Average core recovery (%)	Average RQD (%)	Unconfined compressive strength (PSI)	Tensile strength (PSI)	Moisture content (%)	Specific gravity (PSIx10E6)	Static modulus
			Racine Formation (Silurian System)				
Dolomite	97.5	82.2	9,861	1,535	2.8	2.79	8.36
			Romeo Member of the Joliet Formation (Silurian System)				
Dolomite	99.0	94.9	17,218	2,618	1.7	2.80	11.79
			Margraf Member of the Joliet Formation (Silurian System)				
Dolomite	98.9	94.0	14,918	1,952	1.8	2.71	8.13
			Elwood Formation (Silurian System)				
Dolomite	99.0	91.1	11,158	1,955	1.68	2.80	7.89
			Kankakee Formation (Silurian System)				
Dolomite	98.8	86.5	11,944	1,931	1.20	2.82	8.45
			Wise Lake and Dunleith Formations (Ordovician System, Galena Group)				
Dolomite	98.4	82.5	10,008	1,598	1.5	2.81	8.83
			Platteville Group (Ordovician System)				
Dolomite	98.7	82.1	14,828	1,968	1.1	2.78	9.17

Rock Strength

Strength properties of bedrock vary widely with lithology, structure, discontinuities, and degree of weathering. Laboratory-determined strength values for a given rock type cannot be related directly in many cases to a true field situation because (1) the overall strength of the rock mass is determined by joints and other discontinuities, not just by the strength of intact rock between fractures, and (2) rock that has a tendency to deteriorate upon exposure to air might have a different in situ strength than that determined from laboratory samples. Therefore, laboratory-determined parameters were supplemented by and compared with in situ parameters obtained by geophysical borehole logging, seismic refraction techniques, and in situ testing.

In addition to the summary (table 10) and individual test results (appendix B), average rock properties in the SSC study area are plotted (fig. 13) for Silurian dolomite, Maquoketa shale and dolomite, Galena dolomite and limestone, and Platteville dolomite and limestone.
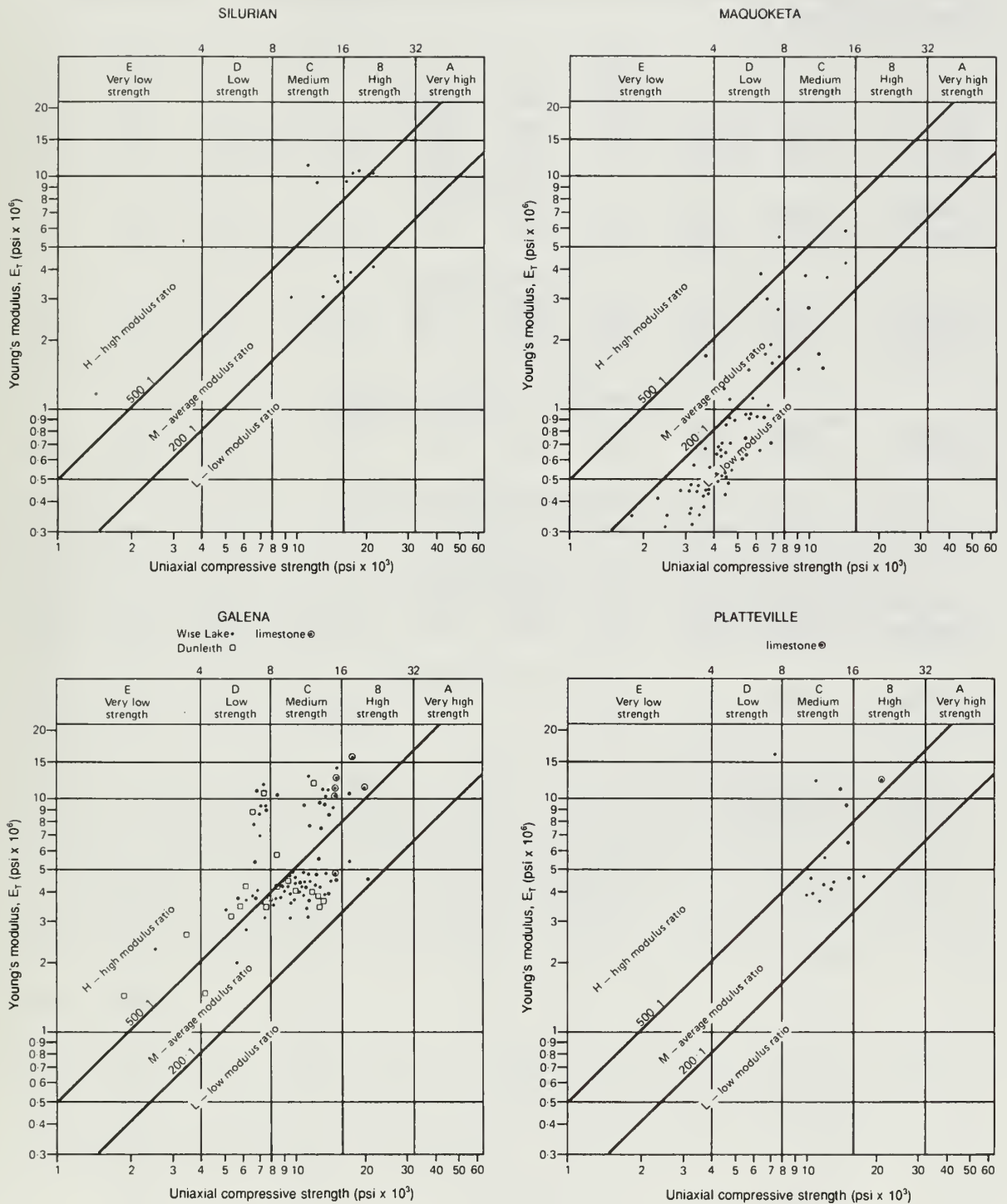
Figure 13 Average rock properties for the Silurian dolomite, Maquoketa shale and dolomite, Galena dolomite and limestone, and Platteville dolomite and limestone.

Table 10 Summary of ISGS geotechnical data for bedrock samples from the SSC study area (average values per borehole).

Rock type	Qu (PSI)	Modulus psix10*6	Axial indirect tensile strength (psi)	Point load index (psi)	Moisture content (W%)	Specific gravity	Shore hardness	Diam. point load index (psi)	Index of aniso-tropy
Silurian System									
Limestone	13,859	6.61	1,002	1,488	2.06	2.68	50	530	2.8
Dolomite	16,341	7.20	1,178	2,299	1.21	2.69	58	656	3.6
Maquoketa Group									
Dolo-Shale	4,405	0.77	523	686	4.22	2.48	27	201	4.2
Dolomite	8,998	3.13	817	1,456	1.62	2.59	52	430	3.3
Limestone	15,805	3.00	1,092	1,537	1.26	2.66	53	617	2.9
Galena Group, Wise Lake Formation									
Dolomite	10,034	5.62	841	1,428	1.58	2.65	57	536	2.8
Limestone	16,148	11.72	1,089	1,974	0.79	2.66	49	609	3.4
Galena Group, Dunleith Formation									
Dolomite	7,600	4.63	635	999	2.89	2.56	49	398	2.6
Platteville Group									
Dolomite	12,169	6.56	1,034	1,601	1.62	2.64	57	747	2.3
Limestone	22,775	6.30	1,411	2,460	0.24	2.69	58	715	3.4
St. Peter Sandstone									
Sandstone	1,795	0.69	120	260	6.62	2.23	12	58	4.5

Table 11 Schmidt Hammer test results for bedrock samples from the SSC study area.

Bore-hole	Depth (ft)	Schmidt (L) Hammer Test (5 highest of 10) Hammer rebound values					Average hr	Corrected hr
		1	2	3	4	5		
F-1	363.5	22	22	20	20	23	21.4	23.9
F-1	341.0	28	33	26	20	18	25.0	27.9
F-3	303.9	39	38	32	31	38	35.6	39.8
F-5	310.4	24	34	24	32	31	29.0	32.4
F-5	456.5	36	30	36	37	32	34.2	38.2
F-7	390.0	31	40	36	35	42	36.8	41.1
F-10	308.0	31	28	29	33	30	30.2	33.7
F-11	188.9	25	29	34	26	31	29.0	32.4
F-11	327.0	42	36	40	38	43	39.8	44.5
F-12	440.0	32	24	26	30	25	27.4	30.6
F-12	471.0	40	33	32	31	42	35.6	39.8
F-16	311.8	28	34	25	25	25	27.4	30.6
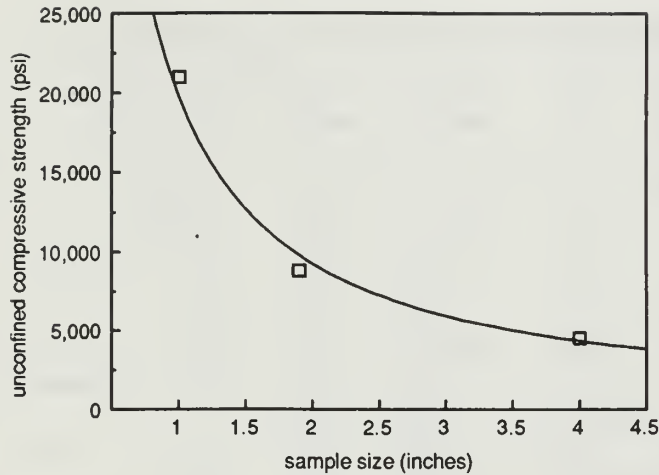
Figure 14 Strength relative to sample size of Wise Lake dolomite samples.

Summaries of rock mechanics tests on core samples taken from SSC test holes F-1 through F-17 are presented in table 10; this table includes the results of point-load tests performed diametrically and axially. According to a classification of point-load strength indices proposed by Broch and Franklin (1972), the SSC samples would fall mostly into a high strength category, with some dolomites extending into a very high strength range and some shales into the medium strength range. All tests were performed according to the standards of the International Society for Rock Mechanics (Brown 1981).

Rock Strength Versus Sample Size

Three sample sizes (1-inch cubes, 1.9-inch-diameter core, and 4-inch-diameter core) of Wise Lake Dolomite were tested for unconfined compressive strength characteristics. A few 1-inch cubes and 4-inch cores were also tested, but they showed the expected decrease in strength (from 21,071 psi to 8,696 psi to 4,593 psi) with increase in sample size (fig. 14). Two of the sample sizes (the 1.9-inch and 4-inch cores) had the same height-to-width ratios of 2; only the 1-inch cubes had a different shape. The controlling strength factor for the Wise Lake dolomite appears to be the vugs it contains: the vuggy sections crushed during many of the tests. Part of the high strength of the 1-inch cube samples can be attributed to the different shape.

Rock Hardness

Rock hardness tests were conducted on samples representing all types of formations. These tests included two types of rebound hardness—Schmidt Hardness (H_R) and Shore Hardness (H_S) (ISRM 1978)—and two types of abrasion hardness, Taber Abrasion Hardness (H_A) (Tarkoy 1975) and Cerchar Abrasivity. Total hardness (H_t) of a sample, a value used to assess the boreability of rocks excavated by TBM, is given by:

$$H_t = H_R \, (H_A)^{1/2}$$

Tables 11 and 12 give the results of Schmidt Hardness and Taber Abrasion tests, and tables 13 and 14 summarize the results of these tests. Cerchar Abrasivity tests were performed on three lengths of Galena (Wise Lake) dolomite core samples by Atlas Copco Roctec. The overall test results showed Cerchar values of 1.4 to 1.6, which are typical for dolomite.

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Table 12 Taber Abrasion test results for bedrock samples from the SSC study area.

Bore hole	Depth (ft)	Test no.	Weight (before)	Weight (after)	Weight loss	Avg. wt. loss	Ha	Ar
F-1	363.5	1	29.429	28.153	1.276			
		2	26.79	24.974	1.816			
		3	28.444	26.75	1.694	1.595	0.626	
Abrasion disk		3	37.478	36.658	0.82	0.82		1.219
F-1	341.0	1	26.415	22.541	3.874			
		2	27.315	23.741	3.574			
		3	22.344	19.604	2.74			
		4	26.602	23.636	2.966	3.288	0.304	
Abrasion disk		3	36.658	36.604	0.054			
Abrasion disk		4	39.632	39.555	0.077	0.0655		15.267
F-3	303.9	1	29.803	28.977	0.826			
		2	29.721	28.759	0.962			
		3	31.675	30.874	0.801	0.863	1.158	
Abrasion disk		3	39.555	39.243	0.312	0.312		3.205
F-5	310.4	1	28.811	27.272	1.539			
		2	29.227	27.921	1.306			
		3	31.482	30.199	1.283	1.376	0.726	
Abrasion disk		3	36.604	36.046	0.558	0.558		1.792
F-5	456.5	1	29.485	28.037	1.448			
		2	29.01	27.199	1.811			
		3	24.773	22.589	2.184	1.814	0.551	
Abrasion disk		2	36.046	34.928	1.118			
Abrasion disk		3	39.243	38.355	0.888	1.003		0.997
F-7	390.0	1	29.957	28.964	0.993			
		2	28.748	27.708	1.04			
		3	21.743	20.736	1.007	1.013	0.986	
Abrasion disk		3	38.335	38.166	0.169	0.169		5.917
F-10	308.0	1	30.518	29.745	0.773			
		2	30.8	29.974	0.826			
		3	31.898	30.895	1.003	0.867	1.152	
Abrasion disk		3	34.928	34.884	0.044	0.044		22.727
F-11	188.9	1	29.538	28.678	0.86			
		2	31.24	30.326	0.914			
		3	29.981	28.963	1.018	0.930	1.074	
Abrasion disk		3	38.166	37.747	0.419	0.419		2.386
F-11	327.0	1	31.978	31.306	0.672			
		2	28.055	27.372	0.683			
		3	28.331	27.419	0.912	0.755	1.323	
Abrasion disk		3	34.884	34.74	0.144	0.144		6.944
F-12	440.0	1	29.32	27.43	1.89			
		2	28.582	27.095	1.487			
		3	27.68	26.096	1.584	1.653	0.604	
Abrasion disk		2	34.74	34.477	0.263			
Abrasion disk		3	37.747	37.55	0.197	0.23		4.347
F-12	471.0	1	24.741	22.945	1.796			
		2	24.373	22.91	1.463			
		3	23.286	21.898	1.388			
		4	21.793	20.272	1.521	1.542	0.648	
Abrasion disk		3	34.477	34.168	0.309			
Abrasion disk		4	37.55	37.107	0.443	0.376		2.659
F-16	311.8	1	28.311	27.155	1.156			
		2	31.259	30.45	0.809			
		3	28.583	27.733	0.85			
		4	35.936	35.14	0.796	0.902	1.107	
Abrasion disk		3	34.168	33.959	0.209			
Abrasion disk		4	37.107	36.919	0.188	0.198		5.037

Tarkoy and Hendron (1975) proposed the following Rock Hardness Classification:

Class	Total Hardness (H_t)
Extremely hard	>200
Hard	150-200
Moderately hard	75-150
Moderately soft	50-75
Soft	25-50
Extremely soft	<25

On the basis of this classification, the following rock units were classified according to rock hardness and TBM performance:

Rock type	Total Hardness (H_t)	Tarkoy-Hendron
Maquoketa shale	15.4	Extremely soft
Galena (Wise Lake) dolomite	30.7	Soft
Galena (Wise Lake) limestone	36.2	Soft
Galena (Dunleith) dolomite	32.3	Soft
Platteville dolomite	37.2	Soft

This classification indicates rock types suitable for rapid TBM excavation. Hardness for each rock type (except the Maquoketa) is virtually the same, which indicates that problems associated with varying rock hardness would be minimal.

Table 13 Summary of data from Schmidt Hammer, Taber Abrasion, and Total Hardness tests, by stratigraphic unit.

Bore-hole	Depth (ft)	Group	Formation	Rock type	Average Schmidt Hammer value (Hr)	Modified Taber Abrasion Hardness (Ha)	Total Hardness
F-1	363.5	Galena	Wise Lake	Dol	23.9	0.627	18.92
F-1	341.0	Maquoketa		Sh	27.9	0.304	15.38
F-3	303.9	Galena	Wise Lake	Dol	39.8	1.159	42.85
F-5	310.4	Galena	Wise Lake	Dol	32.4	0.727	27.63
F-5	456.5	Platteville		Dol	38.2	0.551	28.36
F-7	390.0	Galena	Dunleith	Dol	41.1	0.987	40.83
F-10	308.0	Galena	Wise Lake	Ls	33.7	1.153	36.19
F-11	188.9	Galena	Wise Lake	Dol	32.4	1.074	33.58
F-11	327.0	Platteville		Dol	44.5	1.323	51.18
F-12	440.0	Galena	Dunleith	Dol	30.6	0.605	23.80
F-12	471.0	Platteville		Dol	39.8	0.649	32.06
F-16	311.8	Galena	Dunleith	Dol	30.6	1.108	32.21

Average values by rock unit					Schmidt hammer	Taber abrasion	Total hardness
		Maquoketa		Sh	27.9	0.304	15.38
		Galena	Wise Lake	Dol	32.1	0.897	30.74
			Dunleith	Dol	34.1	0.900	32.28
		Platteville		Dol	40.8	0.841	37.20

Dol = dolomite; Ls = limestone; Sh = shale

Table 14 Average rock property values for bedrock formations in the SSC study area.

| Unit | Core recovery (%) | RQD (%) | Triaxial | | UCS (psi) | Modulus (psix10⁶) | Indirect tensile (psi) | Poisson's ratio (from sonic velocities) |
			Phi	Cohesion (psi)				
Silurian	99.7	98.9	48°	1,640	16,065	7.13	1,159	0.279
Maquoketa	(98.5	97.2	32°	996.)*				
Shale					4,405	0.77	523	0.192
Dolomite					8,998	3.13	817	0.268
Galena								
Wise Lake								
Dolomite	99.9	99.1	49°	1,555	10,034	5.62	841	0.276
Limestone	99.6	99.6	53°	2,842	16,148	11.72	1,089	
Dunleith	99.4	97.6	42°	1,161	7,600	4.63	635	0.269
Platteville								
Dolomite	93.4	89.6	53°	1,884	12,169	6.56	1,034	0.277
Limestone	100	99.7	53°	3,054	22,775	6.30	1,411	

| Unit | Figure 13 | | Velocity ratios $(V_F / V_L)^2$ | Rock mass classification | | Taber Abrasion | Total Hardness |
	Compressive classification	Modulus ratio		Q-System	RMR		
Silurian	Medium-high	Avg-high	0.725	98	80-92		
Maquoketa							
Shale	Very low-avg	Low-avg	0.463	14	52-64	0.304	15.38
Dolomite	Very low-avg	Low-avg	0.532	14	55-67		
Galena							
Wise Lake							
Dolomite	Low-med	Avg-high	0.765	98	75-87	0.897	30.74
Limestone	Med-high	High		98	80-92	1.153	36.19
Dunleith	Very low-med	Avg-high	0.767	96	75-87	0.900	32.28
Platteville							
Dolomite	Medium	Avg-high	0.764	88	72-84	0.841	37.20
Limestone	High	High		98	77-89		

* undifferentiated dolomite and dolomitic shale

Special Testing for Weak Shales

Potentially weak shales and clay layers were subjected to additional tests because of possible impact such layers could have on underground construction. Core recovery and RQD values in shaly units (Maquoketa in particular) were good to excellent; therefore, no special sampling techniques were required to obtain undisturbed samples.

Mineralogic analyses of Maquoketa shale samples revealed no swelling clays; however, the clay fraction of some thin clay-shale beds in the Galena and Platteville Groups contained layers of

Table 15 Slake durability and Atterberg Limits* values for Maquoketa Shale in the SSC study area.

Borehole	Depth to sample (ft)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Slake durability 1st cycle (%)	Slake durability 2nd cycle (%)	USCS
F-1	302	26.6	16.7	9.9	--	--	CL
F-1	316	28.6	17.8	10.8	--	--	CL
F-2	330	29.2	19.4	9.8	--	--	CL
F-2	360	28.1	18.3	9.8	96.4	94.6	CL
F-2	360	30.1	18.9	11.2	92.4	89.6	CL
F-3	220	33.7	20.4	13.3	94.9	88.3	CL
F-6	309	36.1	21.2	14.9	69.3	38.3	CL
F-7	202	28.0	18.5	9.5	94.5	87.4	CL
F-10	246	30.5	20.7	9.8	97.0	91.1	CL
F-10	253	27.4	19.0	8.4	97.3	90.7	CL

*Atterberg limits performed on shale samples that passed #40 mesh sieve and were cured for 2 weeks.

well-ordered, mixed-layered illite/smectite; this mixed-layer assemblage contains 20 to 27 percent smectite layers. The smectite has an inherent swelling capacity but is a minor fraction of the clay material. Relatively few of these clay-shale beds occur in the dolomites, and they are very thin—usually less than 1 inch thick.

Maquoketa shale samples were also tested for unconfined swelling strain and Atterberg Limits of disintegrated material (table 15). The average liquid limits of disintegrated shale were below 30 percent and, therefore, according to the criteria of Brekke and Howard (1973), should not pose a swelling problem. The swelling test performed at natural moisture content showed approximately 1 percent strain after being submerged for 1 month. Swelling pressure tests utilizing constant volume approach through zero deflection of the sample were performed on two Maquoketa shale samples; one sample was from a surface quarry operation, the other from a drill core. The quarry sample produced maximum swelling pressures of 11,600 pounds per square foot (psf) within 17 hours. The core sample produced a maximum swelling pressure of 80,100 psf within 32 hours. Tests were conducted in accordance with ASTM D 4546, Method C. Additional swelling pressure information and general characteristics of the Maquoketa are found in an article by Preber (1984) concerning the Maquoketa shale in northwestern Illinois.

Slake durability tests were performed on shale samples according to the procedures suggested by ISRM (1979). The shales have a medium to medium-high slake durability (fig. 15).

Joints

Joint sets (sets of parallel fractures or breaks in the rocks) in northern Illinois exhibit consistent directions: the primary joint set strikes northwest and the secondary set strikes northeast (fig. 11). In the area for the proposed SSC, three angled boreholes (F-8, S-25, and S-29) were drilled at a dip of 70°. Figure 12 shows the joint directions encountered in these boreholes.

Most of the joints noted in boreholes and rock quarries for the SSC investigation were nearly vertical; 75 to 85 percent of all joints in the dolomites had dips greater then 70° (table 3 and

SLAKE DURABILITY
Maquoketa samples
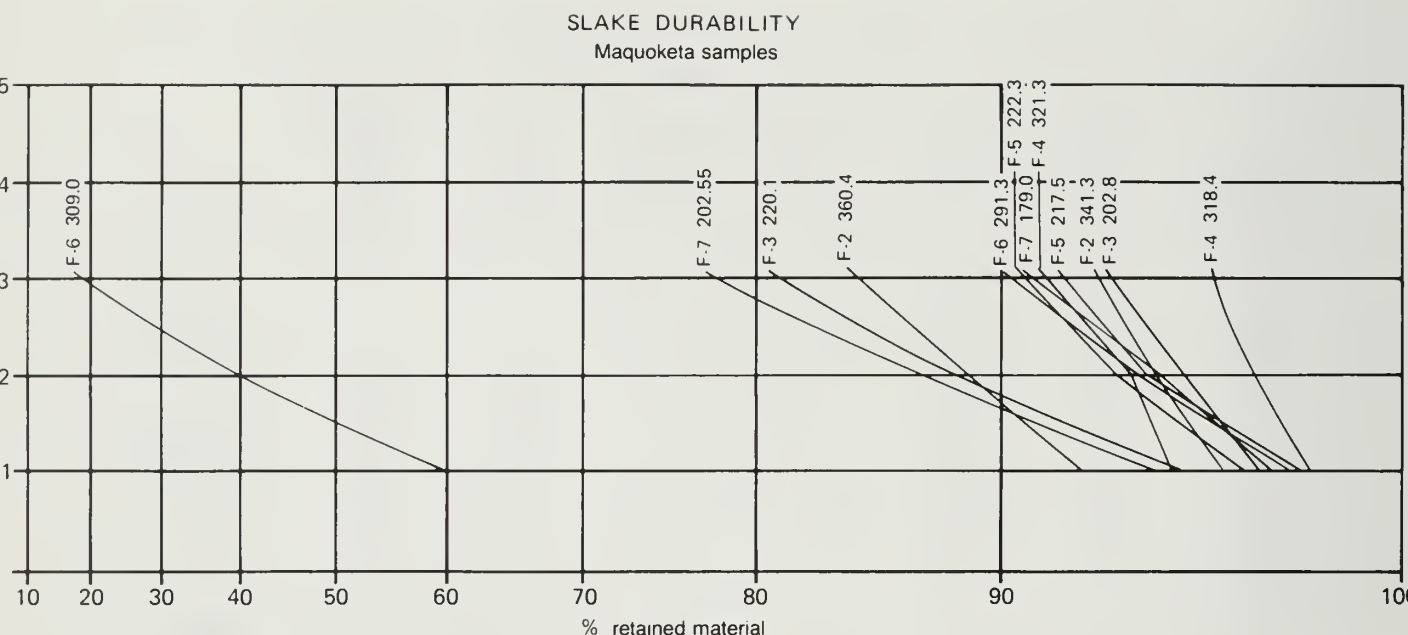
Figure 15 Slake durability values for Maquoketa shale samples, indicating medium to medium-high resistance to slaking.

fig. 16). The joints found during the SSC exploration in Kane, eastern De Kalb, and western Du Page Counties contained very little filling. Only 10 to 19 percent of the joints had complete infilling of clay, calcite, or pyrite. Forty-four to 74 percent of the joints (per formation) contained no infilling material (table 4 and fig. 17). Only 3 to 13 percent of the joints were planar; the rest were wavy and uneven (table 4 and fig. 18). Eighty-seven to 97 percent of the joint walls were sound and unaltered (not weathered, table 4). On the basis of the joint characteristics described, the joints in the SSC study area are strong and interlocking.

The joints described for the TARP project (Harza 1975a) exhibited some of the same characteristics. The most highly developed joint set trends N50°-N60°E, and another set trends from N25°W to N65°W. The northeast set is dominant in the Lawrence and Southwest Tunnels, and the northwest set is dominant in the Calumet Tunnel. The joints are steeply dipping to vertical. Joints are open near the bedrock surface and are locally iron-stained to a depth of 200 feet. In the Addison to Wilmette tunnel, the northwest set is the dominant joint set; it is generally filled with clay-shale (Weiss-Malik and Kuhn 1979). Clay filling is less common in the northeast set, and this joint set is the principal source of water inflows into the tunnel.

Typical joint roughness found in the Galena and Platteville dolomites—assessed by the Joint Roughness Coefficient (JRC) developed by Barton and Choubey (1977)—is shown as joint profiles in figure 19. The JRC scale was developed to describe the roughness on a sample 10 cm (4 inches) long. The values from the smoothest to the roughest discontinuities range from 1 to 20. A system was proposed for relating JRC to maximum joint amplitude (Bandis 1980). JCR determined by this method (fig. 20) ranges from 16 to 20. These JRC values indicate and confirm the visual appearance (fig. 21) of the joints as fractures produced in tension. These values indicate the most desirable joint surfaces for underground construction; rough joint surfaces do not allow blocks of rock to slip out easily.

Joint strength was also tested by using direct shearing of matching joint halves that had no filling material. Three large displacement direct-shear tests on joints in the Galena and Platteville showed peak ϕ values ranging from 15.7° to 20.5° and residual ϕ values ranging from 6.7° to 8.9° (figs. 22, 23, and 24). The procedures outlined in Brown 1981 (p. 135-137) were followed for the testing.

Joint spacing is another important parameter for stability during underground construction. Determining the actual joint frequency of near-vertical joints in vertical boreholes is nearly impossible, so angle boreholes and information from excavations such as underground quarries and previous tunneling projects are used to estimate joint frequency. Angle boreholes do not produce a realistic picture of joint spacing, because the persistence of the joint plane cannot be measured or estimated. Spacings much greater than the width of the underground opening are desirable for more stable conditions.

Examination of joints in a nearby underground quarry 500 feet deep excavated in the Galena revealed that most closely spaced joints are only 1.5 to 12 feet long, but persistent joints are spaced as much as 100 feet apart or more. On a large scale, the joints have wave-lengths of about 13 to 20 feet and amplitudes of about 0.5 to 1.0 foot. Smaller scale wave-lengths of about 1.5 to 3.5 feet have amplitudes of about 0.1 to 0.2 foot; these amplitudes correspond to inclination values ranging from 9° to 15°.
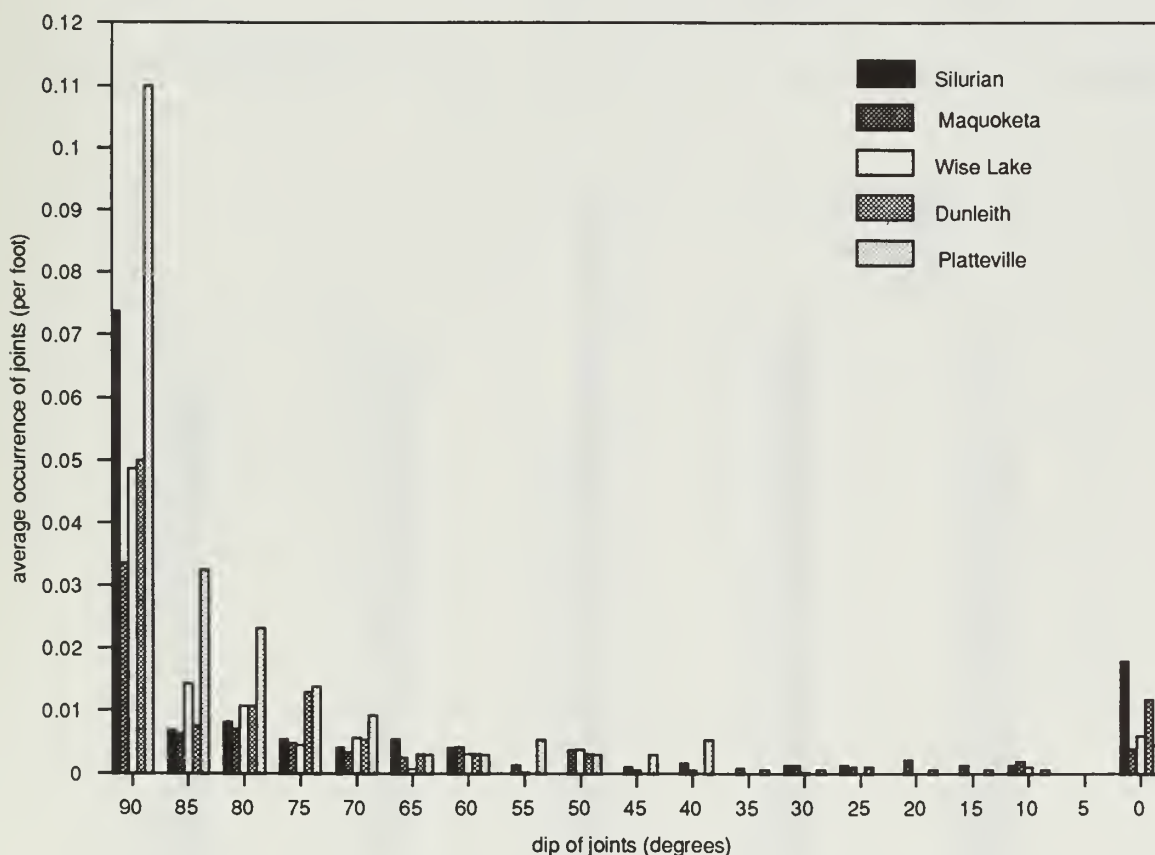
Figure 16 Average occurrence of joints (per ft of core) per formation per dip degree angle of joint in SSC study area.
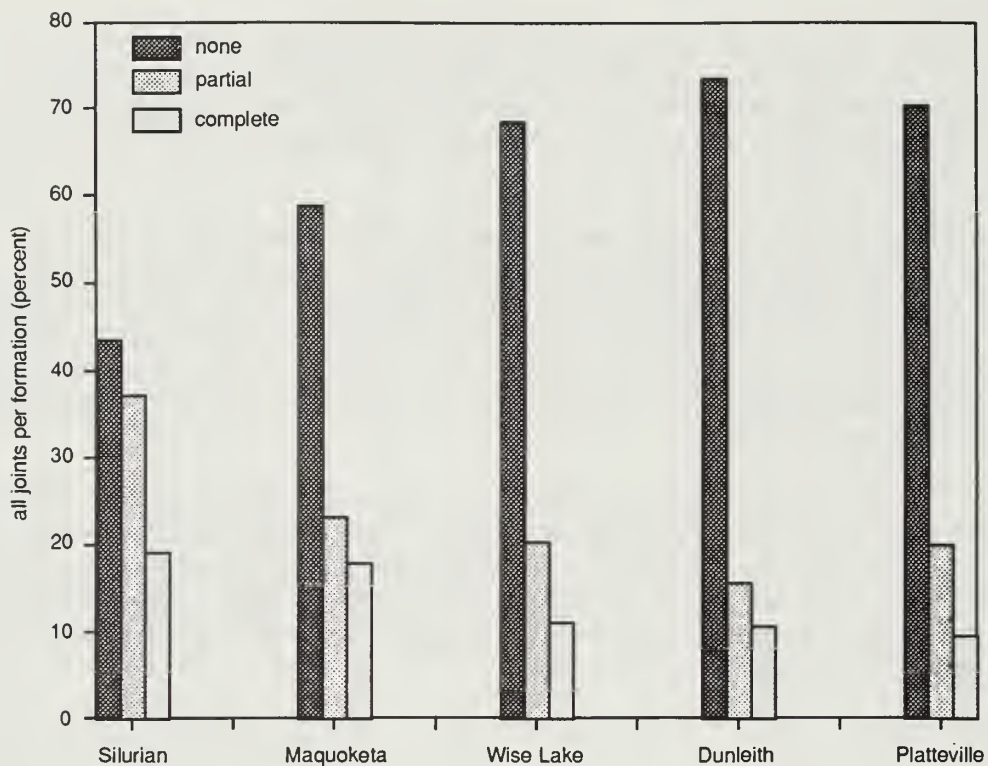
Figure 17 Frequency of type of filling (none, partial, complete) in joints per formation in SSC area.
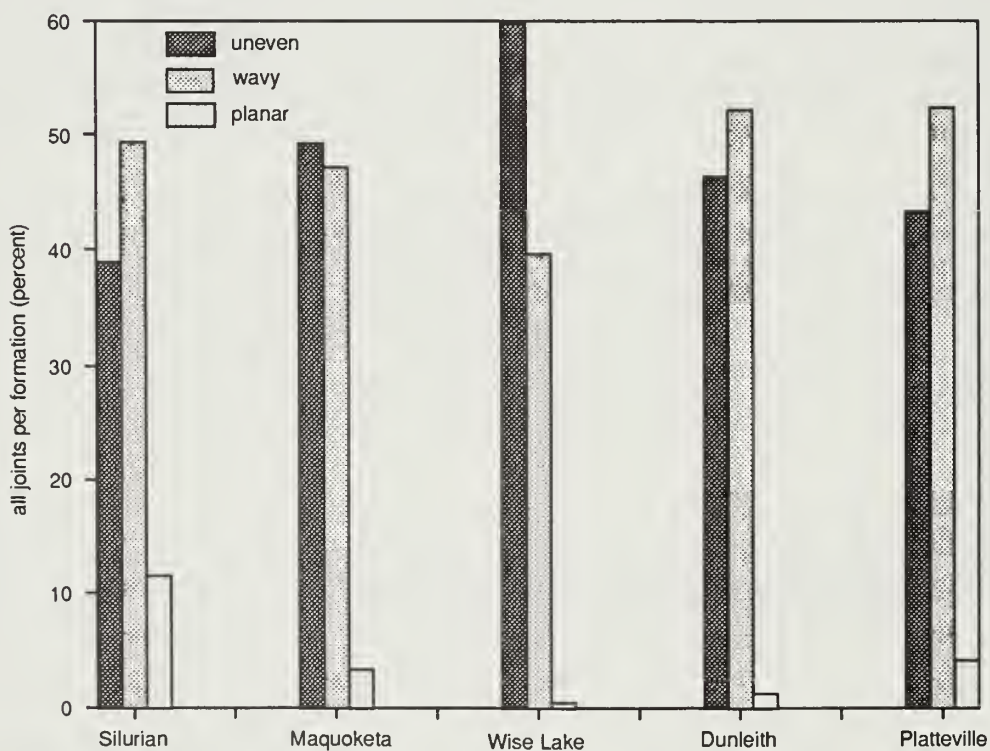
Figure 18 Frequency of type of joints surface, per formation, in SSC study area.

S-20 387.55 ft

S-20 374.8 ft

S-22 219.2 ft

S-26 340.65 ft

1 inch

1 inch
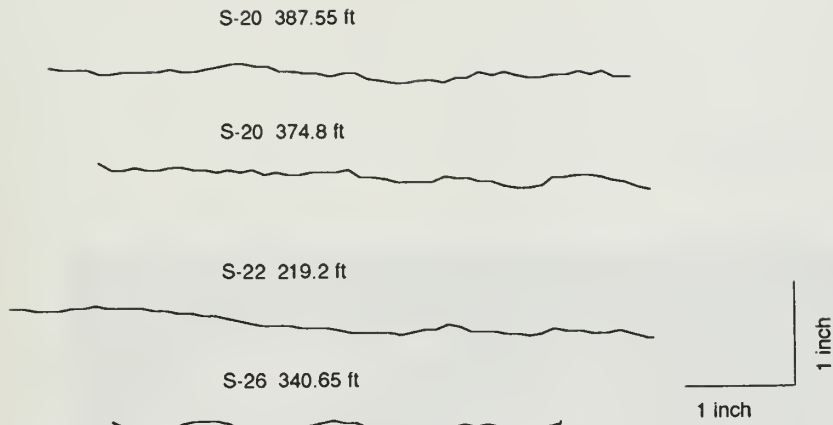
Figure 19 Example of joint face roughness as shown by joint profiles in Wise Lake dolomites of SSC study area.

amplitude

length

amplitude of asperities (mm)

length of profile (m)

joint roughness coefficient (jrc)
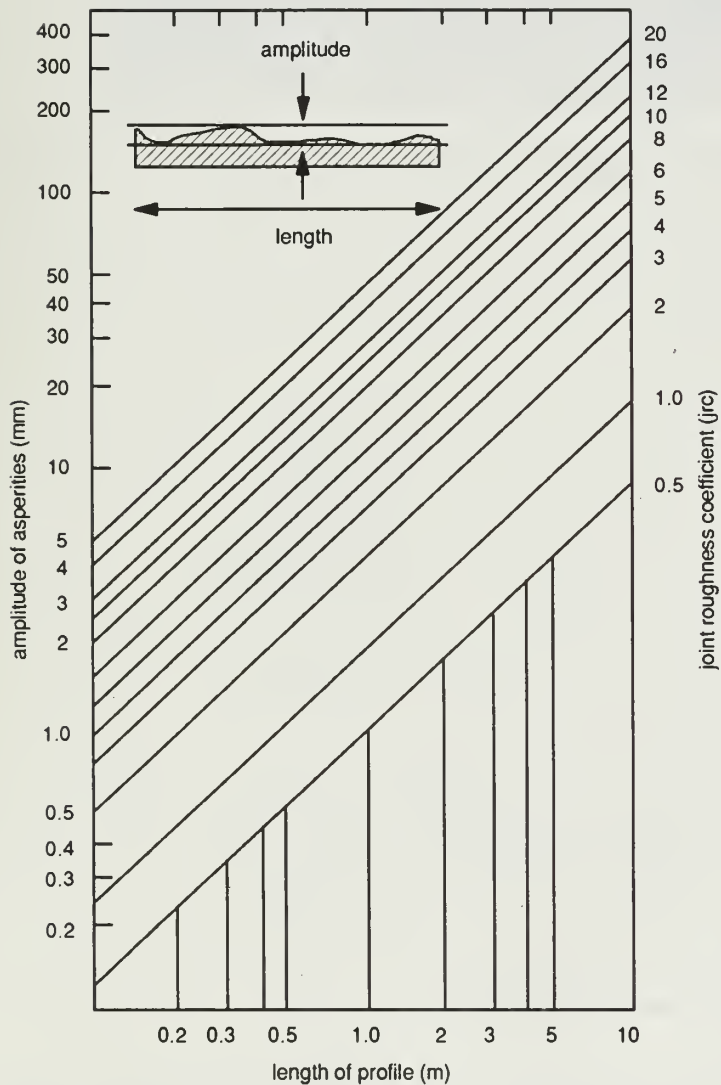
Figure 20 Nomograph to calculate Joint Roughness Coefficient (JRC) (Bandis 1980).
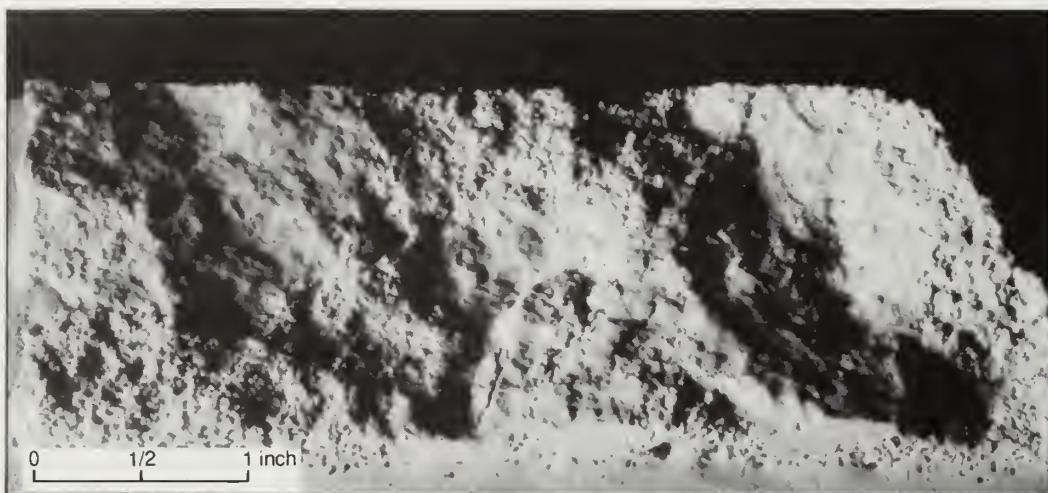
Figure 21 Typical joint face in dolomites of SSC study area.
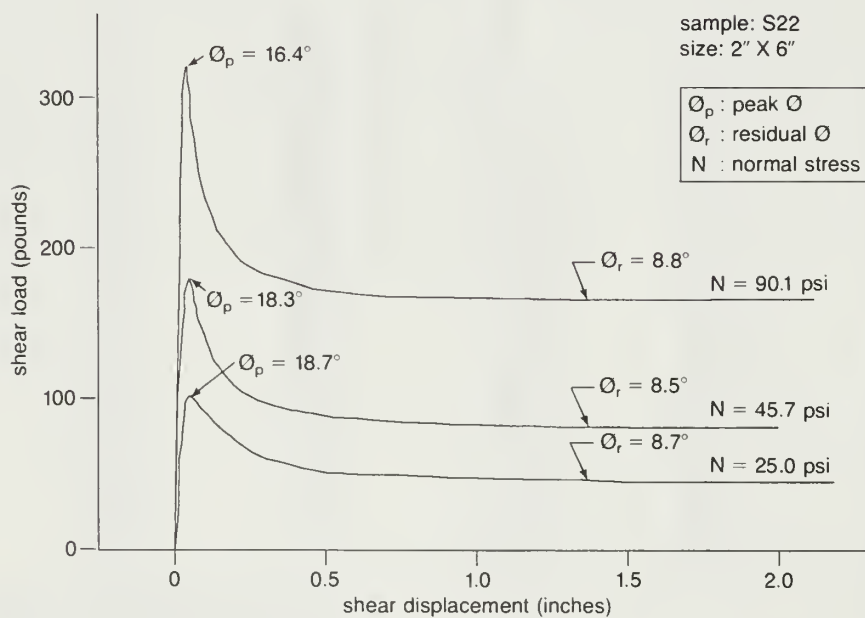
Figure 22 Large displacement direct shear test results for joint in dolomites of SSC area.
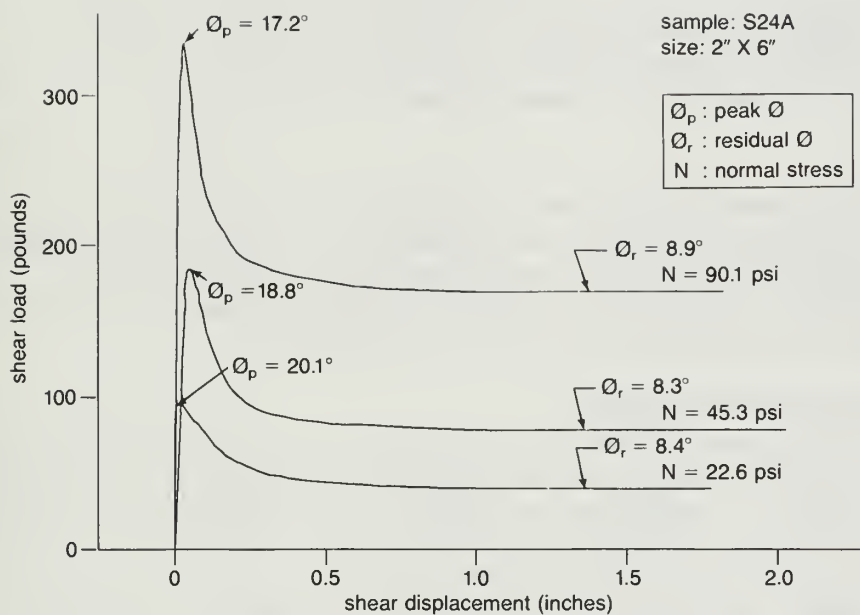
Figure 23 Large displacement direct shear test results for joint in dolomites in SSC area.
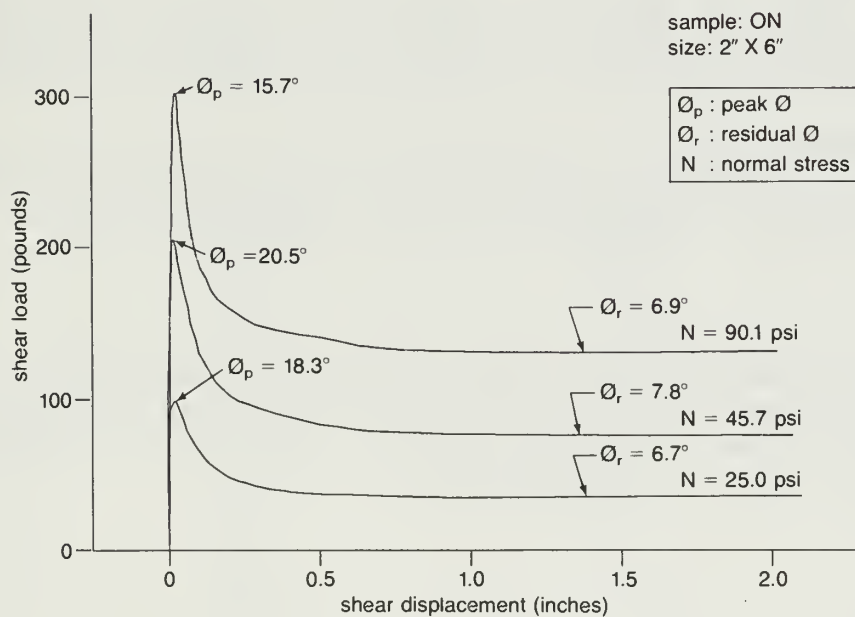
Figure 24 Large displacement direct shear test results for joint in dolomites of SSC area.

Study of joints in seven TARP tunnels (Harza 1984) totaling about 21 miles in length revealed that persistent joints in the northeast-trending set have an average frequency of 321 feet (standard deviation, 216 ft) and those in the northwest-trending set have an average frequency of 143 feet (standard deviation, 70 ft). The combined average frequency of both joint sets in these tunnels was 92 feet (standard deviation, 42 ft). In these tunnels, the frequency of significant joints was several tens to hundreds of feet. Foote (1982) found that the joint spacing in four surface quarries in the Silurian dolomites ranged from 10 to 30 feet.

Sonic Velocities

In situ and laboratory-derived sonic velocities of samples from the SSC study area were measured. In situ measurements (table 16) were made in the three large-diameter boreholes (Vaiden et al. 1988), and laboratory measurements were made on core samples from boreholes F-1 through F-17 (table 17). The ratio between field and laboratory values produced information on rock mass properties discussed in the following section.

Rock Mass Properties and Classification

In addition to the general absence of faulting or other adverse structures, the excellent quality of the rock mass is typified by the high core recovery and RQD values for each of the formations penetrated in the SSC exploratory drilling program. Average core recovery and RQD values are shown in tables 18 and 19 and summarized in table 14. Lowest core recovery and RQD values for stratigraphic units in each borehole are listed in tables 20 and 21; most of these values are greater than 90 percent, indicating very sound rock. The anomalously low values found in one run of drillhole F-13 and two runs of F-17 are most likely not due to poor rock conditions but to mechanical breaks along two intersecting vertical joints.

The squared ratio between the seismic wave velocity in the field (V_F) and the sonic wave velocity measured in the laboratory (V_L) is used as an index of rock mass quality (Coon and Merritt 1970). Ratios between sonic velocities measured in the field and laboratory $(V_F/V_L)^2$ (table 14) indicate good rock mass quality in the Silurian, Galena, and Platteville, and fair quality in the Maquoketa.

A classification of predicted rock mass condidtions determined by the method of Barton et al. (1974) is presented in table 22 and plotted in figure 25. Q-values range between 14 (good) for the Maquoketa and 94 (very·good) for the Silurian and Galena and Platteville formations.

Application of Bieniawski's (revised 1979) rock mass rating (RMR) for the most probable rock mass conditions produced RMR values of 52 to 64 (fair to good) for the Maquoketa, 72 to 87 (good to very good) for the Galena and Platteville, and 80 to 92 (good to very good) for Silurian formations (table 23). A compilation of classification systems appears in Bieniawski (1989).

On the basis of the RMR and Q values, probable tunneling conditions are fair to good in the Maquoketa shale and good to very good in all other units (dolomites and limestones). Both methods not only predict good quality rock and favorable tunneling conditions but also indicate that tunnels in these units would require little or no support—the same conditions predicted and encountered with TARP rock tunnel construction.

Table 16 Average in situ sonic velocities and calculated Dynamic Moduli values of bedrock in the SSC study area.

	Compressive wave velocity (ft/sec)	Shear wave velocity (ft/sec)	Poisson's ratio	Shear modulus (10^6psi)	Bulk density (g/cc)
BOREHOLE SSC 1, Kaneland					
Galena					
Wise Lake	16,048	8,811	0.273	2.75	2.639
Dunleith	15,741	8,832	0.267	2.76	2.623
Platteville	17,000	9,411	0.277	3.22	2.695
St. Peter	10,804	6,245	0.245	1.21	2.294
BOREHOLE SSC 2, Fermilab					
Silurian	15,787	8,711	0.279	2.74	2.688
Maquoketa					
Shale	9,098	5,542	0.195	1.04	2.528
Dolomite	12,276	6,896	0.268	1.65	2.584
Galena					
Wise Lake	18,124	10,065	0.276	3.68	2.697
Dunleith	16,920	9,496	0.268	3.21	2.638
Platteville	17,688	9,789	0.278	3.46	2.695
St. Peter	12,176	6,929	0.258	1.54	2.377
BOREHOLE SSC 3, Big Rock					
Maquoketa					
Shale	8,681	5,368	0.188	0.97	2.511
Dolomite	11,398	7,110	0.180	1.78	2.615
Galena					
Wise Lake	17,751	9,801	0.279	3.50	2.679
Dunleith	17,374	9,686	0.273	3.37	2.669
Platteville	17,150	9,543	0.275	3.29	2.682
St. Peter	11,272	6,615	0.235	1.37	2.326

	Average field compressive wave velocity (ft/sec)	Average lab compressive wave velocity (ft/sec)	Ratio field/lab
Silurian	15,787	18,538	0.85
Maquoketa			
Shale	8,916	13,091	0.68
Dolomite	12,245	16,782	0.73
Galena			
Wise Lake	17,535	20,046	0.87
Dunleith	16,654	19,015	0.87
Platteville	17,284	19,772	0.87

Table 17 Laboratory-measured compressive wave velocities (units in ft/sec), parallel (par) and perpendicular (per) to bedding, in samples from SSC boreholes.

Bore-hole	Silurian			Maquoketa Dolo-shale			Maquoketa Dolo		Maquoketa Ls		Wise Lake Dolomite			Dunleith Dolomite			Platteville Dolomite		
	No. of tests	par	per	No. of tests	par	per	No. of tests	par	No. of tests	par	No. of tests	par	per	No. of tests	par	per	No. of tests	par	per
F-1	6	17,359	15,992	11	13,307	11,309	4	17,070			5	20,406	18,954						
F-2	4	20,674	17,289	14	12,504	9,743	2	16,335			13	20,378	19,128						
F-3				8	13,519	10,919					5	19,217	18,196						
F-4	2	19,513	17,092	9	13,094	10,603	5	18,887			4	19,503	18,633						
F-5				3	13,789	10,148					8	19,491	18,845	4	19,269	18,687	3	17,918	15,913
F-6	3	18,314	16,824	5	13,201	10,250	3	15,269			4	20,179	19,283						
F-7	1	16,624	15,043	2	14,245	11,079	3	14,546			5	20,365	18,480	3	20,074	18,814			
F-9							3	16,939			4	20,697	16,798	8	18,548	16,500			
F-10	3	18,124	16,035	3	11,342	8,074					4	19,889	17,013						
F-11											6	19,721	18,055	3	17,946	17,015	6	21,026	19,341
F-12									3	20,471	5	18,012	16,219	3	17,610	15,919	3	18,043	16,182
F-14											3	19,751	18,377	2	19,418	17,341	4	19,393	17,723
F-15				5	13,505	10,589			1	17,726	7	21,163	19,809						
F-16				2	13,398	10,458			3	15,806	7	20,542	18,729	1	20,385	19,053			
F-17											6	20,416	18,848	2	21,406	18,839	4	20,959	19,021
Mean velocities		18,517			13,091			16,782		18,080		20,046			19,015			19,772	

Table 18 Average core recovery values (%), by stratigraphic unit for individual boreholes in the SSC study area.

Bore-hole	Core runs	Silurian	Core runs	Maquoketa	Core runs	Galena (Wise Lake)	Core runs	Galena (Dunleith)	Core Runs	Platteville	Core runs	St. Peter
F-1	14	99.66	16	99.26	14	99.93	1	99.00				
F-2	2	99.90	23	99.80	6	99.90						
F-3			12	99.40	9	99.80						
F-4	2	100.00	21	99.40	2	100.00						
F-5			6	99.91	14	100.00	6	100.00	2	98.00		
F-6	7	99.60	15	98.60	3	100.00						
F-7	2	100.00	13	99.65	14	100.00	3	99.33				
F-8			18	97.10	14	99.90						
F-9			8	98.91	15	100.00	5	99.60	5	99.80		
F-10	3	100.00	16	99.50	13	99.64						
F-11					13	100.00	4	96.87	16	100.00		
F-12			16	97.39	15	100.00	5	100.00	2	100.00		
F-13			7	83.71								
F-14			1	100.00	16	99.84	5	100.00	9	100.00		
F-15			16	99.50	12	100.00						
F-16			12	99.58	12	99.83						
F-17					10	99.60	5	100.00	18	81.27	22	94.54
S-18	4	99.64	17	99.98	14	98.99	5	100.00	1	100.00		
S-19			8	99.22	14	100.00	5	99.62	5	97.93		
S-20	2	100.00	16	99.91	15	99.94						
S-21			6	97.22	15	99.86	5	100.00	4	99.66		
S-22	8	98.76	14	99.96	15	99.41	5	100.00	1	100.00		
S-23			12	99.57	15	99.59	4	100.00	15	100.00	1	90.65
S-24			13	98.73	8	99.88						
S-24A			14	100.00	14	100.00	4	100.00	9	97.81		
S-25	3	97.88	16	99.75	14	98.43	6	97.71	16	99.80	2	90.64
S-26			12	100.00	10	100.00	9	99.01	7	99.24		
S-27	4	99.74	16	99.93	15	100.00	5	100.00	8	99.94		
S-28	8	99.23	17	99.87	14	100.00	4	100.00	4	100.00		
S-29	14	99.27	16	99.64	17	99.56	4	100.00	5	100.00		
S-30	4	99.59	14	99.96	15	99.61	5	100.00	15	99.63	1	94.00

Mean core recovery per stratigraphic unit

		99.42		99.08		99.77		99.56		97.27		94.07

Table 19 Average rock quality designation (RQD) values (%), by stratigraphic unit, for boreholes in the SSC study area.

Bore-hole	Core runs	Silurian	Core runs	Maquoketa	Core runs	Galena (Wise Lake)	Core runs	Galena (Dunleith)	Core Runs	Platteville	Core runs	St. Peter
F-1	14	97.96	16	97.33	14	99.57	1	99.00				
F-2	6	99.90	21	96.50	5	99.90						
F-3			10	99.30	9	99.80						
F-4	2	100.00	21	98.70	2	100.00						
F-5			6	97.25	14	99.85	6	99.00	2	98.00		
F-6	7	98.70	16	97.90	3	99.30						
F-7	2	100.00	13	99.65	14	99.42	3	97.00				
F-8			19	98.00	14	98.80						
F-9			8	97.40	15	99.60	5	94.60	5	99.80		
F-10	3	100.00	16	98.84	13	99.64						
F-11					13	96.57	4	93.55	16	98.56		
F-12			14	97.39	15	99.53	5	99.20	2	100.00		
F-13			7	70.14								
F-14			1	100.00	16	99.34	5	98.20	9	98.44		
F-15			16	99.50	12	98.58						
F-16			12	99.58	12	99.83						
F-17					10	96.70	5	100.00	19	73.36	22	94.54
S-18	4	99.64	17	99.98	14	98.99	5	99.47	1	100.00	0	
S-19	0		8	98.65	14	100.00	5	99.59	5	99.13	0	
S-20	2	100.00	16	99.60	15	99.94	0		0		0	
S-21	0		6	72.44	15	99.86	5	99.56	4	99.66	0	
S-22	8	67.46	14	99.96	15	99.09	5	100.00	1	100.00	0	
S-23	0		12	98.56	15	99.44	4	100.00	15	95.07	1	90.65
S-24	0		13	97.59	8	99.29	0		0		0	
S-24A	0		14	98.31	14	99.28	4	99.68	9	97.00	0	
S-25	3	93.92	16	89.45	14	90.85	6	89.31	16	97.36	2	90.64
S-26	0		12	99.36	10	95.29	9	89.13	7	92.46	0	
S-27	4	98.57	16	99.73	15	99.73	5	99.55	8	99.88	0	
S-28	8	96.81	17	99.20	14	100.00	4	100.00	4	99.93	0	
S-29	14	95.21	16	98.82	17	97.82	4	94.99	5	100.00	0	
S-30	4	99.59	14	99.80	15	99.48	5	98.80	15	98.80	1	94.00

Mean RQD per stratigraphic unit

		94.84		97.38		98.83		97.05		94.62		94.07

Table 20 Lowest core recovery values (%), by stratigraphic unit, for individual boreholes in the SSC study area.

| Borehole | Silurian | Maquoketa | Galena | | Platteville | St. Peter |
			Wise Lake	Dunleith		
F-1	97	96		99		99
F-2	99	98	99			
F-3		96	99			
F-4	100	95	100			
F-5		99	100	100	98	
F-6	97	84	100			
F-7	100	98	100	98		
F-8		91	99			
F-9		97	100	98	99	
F-10	100	96	98			
F-11			100	90	100	
F-12		70	100	100	100	
F-13		41				
F-14		100	97	100	100	
F-15		96	100			
F-16		97	98			
F-17			96	100	18	60
S-18		97	100	89	100	
S-19	96	100	98	98		
S-20	100	99	97	99		
S-21	85	98	100	99		
S-22	90	99	97	100	100	
S-23	98	97	100	100	90	
S-24	85	97				
S-24A	100	100	100	87		
S-25	91	99	85	98	90	87
S-26	100	100	87	100		
S-27	98	99	100	100	99	
S-28	96	98	100	100	100	
S-29	74	98	97	98	100	
S-30	99	99	95	100	100	94

Table 21 Lowest rock quality designation (RQD) values (%), by stratigraphic unit, for boreholes in the SSC study area.

| Borehole | Silurian | Maquoketa | Galena | | Platteville | St. Peter |
			Wise Lake	Dunleith		
F-1	90	65	95	99		
F-2	99	64	99			
F-3		88	99			
F-4	100	91	100			
F-5		84	98	96	98	
F-6	95	84	98			
F-7	100	98	92	93		
F-8		91	75			
F-9		90	94	75	99	
F-10	100	92	99			
F-11			80	84	88	
F-12		70	97	98	100	
F-13		0				
F-14		100	98	97	93	
F-15		96	94			
F-16		97	98			
F-17			88	100	0	60
S-18	97	99	89	97	100	
S-19		94	100	98	91	
S-20	95	96	99			
S-21		0	98	98	98	
S-22	0	99	95	100	100	
S-23		95	96	100	77	90
S-24		85	97			
S-24A		94	91	98	87	
S-25	84	0	69	96	31	83
S-26		90	69	68	91	
S-27	94	98	98	98	99	
S-28	91	94	100	100	99	
S-29	74	92	96	94	92	
S-30	99	97	95	94	93	94

Table 22 Most probable rock mass conditions in SSC study area (prediction method, Barton et al. 1974).

	Silurian	Maquoketa	Galena-Platteville
RQD = Rock quality designation	95	95	95
J_n = Joint set number	4	4	4
J_r = Joint roughness number	3	3	3
J_a = Joint alteration number	1	1	1
J_w = Joint water reduction factor	0.66	1	0.66
SRF = Stress reduction factor	0.5	5	0.5
ESR = Excavation support ratio	0.8	0.8	0.8
Q =	94.1	14.2	94.1
Classification =	Very good	Good	Very good

Table 23 Most probable rock mass conditions in study area (predicted by Bieniawski's revised (1979) method).

	Silurian	Maquoketa	Galena-Platteville
Rock strength	12	4	17 to 20
RQD	20	20	17 to 20
Spacing of discontinuities	20	20	20
Condition of discontinuities	30	10	30
Groundwater	10	10	10
Strike and dip of discontinuities	0 to −12	0 to −12	0 to −12
Rating	80 to 92	52 to 64	72 to 87
Classification =	Good to very good	Fair to very good	Good to very good

In Situ Stresses

In situ rock stress was measured, using the hydrofracturing technique, in Kane and western Du Page Counties. Results obtained from 13 individual tests in two holes covered the units from the Maquoketa down through the Platteville.

The maximum principal stress (σ_1) is horizontal and oriented N55-65°E (Haimson 1987). The maximum, major principal stress obtained from the mean of two adjacent tests in the Dunleith Formation is about 1,700 psi. The intermediate principal stress (σ_2) is also horizontal, and is oriented N25-35°W. The maximum, intermediate principal stress, determined from the same two tests noted above, is about 1,000 psi. In the Wise Lake Formation and Platteville Group, mean measured values of σ_1 and σ_2 did not exceed 1,575 and 860 psi respectively. No horizontal stresses could be measured in the Maquoketa shale. In general, the ratio of horizontal to the assumed, estimated vertical in situ stresses varies between 1:1 and 5:1, and the ratio of maximum to minimum horizontal in situ stress (σ_1/σ_2) varies between 1.5:1 and 2:1. Tables 24 and 25 show the results of the in situ stress tests in the two boreholes.

The σ_3 stress, minor principal stress, is assumed to be vertical in all formations. In situ stress measurements in the Maquoketa produced only horizontal fractures, which indicates that the vertical stress averages 1.23 psi per foot of depth.

Nearby in situ stresses were measured for TARP at the Calumet pumping caverns in the Silurian dolomite (Shuri and Kelsay 1984). Thirty-four successful overcoring tests were performed in 5 nonparallel boreholes drilled from an exploratory adit at the level of the cavern, about 300 feet below the ground surface. The maximum horizontal stress, four times the vertical stress, strikes about N72°E. The minimum principal stress is 493 psi and dips 45°.

GEOTECHNICAL CHARACTERISTICS OF UNDERGROUND FACILITIES IN NORTHEASTERN ILLINOIS

This section summarizes the principal geologic and geotechnical characteristics that would affect the siting of underground facilities in the bedrock of northeastern Illinois.

Rock Formations

The strata dip very gently toward the east, and most of the rock units are relatively homogeneous. Thus, except in some areas of the Maquoketa Group, tunnels can follow single rock types full-face over considerable distances.

Tunneling Conditions

Rock conditions in the area are eminently suitable for excavation by TBM. Local tunnel segments to install the TBMs, intersections, and bypasses can be excavated by the drill-and-blast method. Tunneling conditions can be expected to be good to excellent on the basis of the evaluation of the accumulated knowledge and data presented earlier in this report, including:

Table 24 In situ stress calculations for SSC borehole S-26.

Test	Depth ft	Rock unit	Sv(gr) psi	Sv psi	Sh psi	SH psi	SH direction
1	186	MS	190	320			
9	244	MS	250	310			hor frac
2	265	WLD	275				
3	303	WLD	320		500	885	N54°E
4	331	WLD	350		470	710	
5	382	DD	435		695	1235	N54°E
8	452	PD	495		585	1115	
7	466	PD	500		620	1170	
6	481	PD	515		580	1045	N53°E

Table 25 In situ stress calculations for borehole S-28.

Test	Depth ft	Rock unit	Sv(gr) psi	Sv psi	Sh psi	SH psi	SH direction
1	75	SD	70		155	325	
11	147	SD	155		560	840	N69°E
2	200	MS	215	200			
10	217	MS	230	320			hor frac
3	250	MS	270	300			hor frac
9	277	MS	300	340			
4	321	WLD	344		960	1715	N63°E
8	377	WLD	410		800	1440	N57°E
5	441	WLD	480		815	1575	
7	457	DD	500		830	1485	
6	466	DD	510		1150	1970	N65°E

Sv(gr) =	calculated vertical stress from rock density	MS =	Maquokets Shale
Sv =	vertical stress based on the shut-in pressure valve in horizontal hydrofractures	WLD =	Wise Lake Dolomite
		DD =	Dunleith Dolomite
Sh, SH =	least horizontal and largest horizontal principal stresses	PD =	Platteville Dolomite
SD =	Silurian Dolomite	hor frac =	horizontal fracture
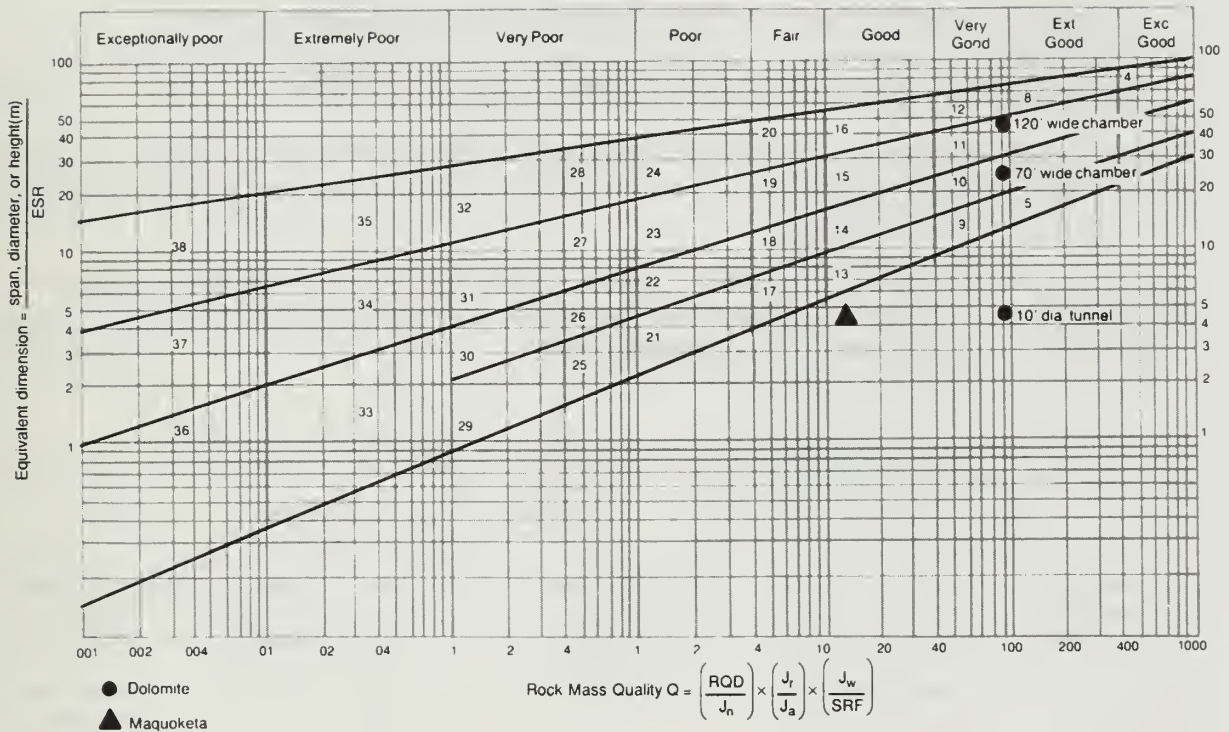
Figure 25 Barton's Rock Mass Classification by bedrock unit for the most probable underground conditions in the SSC study area.

- excellent RQD values: 90 percent or greater in all formations;
- high Q values of Barton's et al. (1974) rock mass classification;
- good to very good rock mass rating using Bieniawski's (1979) RMR classification;
- absence of known faults or other adverse geologic structures (i.e., squeezing ground sensitive clays, soil conditions);
- absence of toxic or flammable gases;
- proven excellence in tunneling through the dolomite formations in the region.

Chambers

Chambers should be oriented nearly north-south. This orientation bisects the angle between the two major joint sets; consequently, joints in the chamber walls are intercepted at the widest angle, which provides the greatest possible sidewall stability.

Roof Span

Rock stresses around the proposed underground chambers were assessed. This sensitivity analysis included a range of practical cavern roof spans (50, 75, 100, and 125 feet) and varied horizontal to vertical stress ratios ranging from 2 to 4. Results of the finite element analysis are included in a published report prepared by Harza Engineering Company for the Illinois Department of Energy and Natural Resources (July 1986). The following general conclusions were reached:

- All studied conditions for 75-foot high chambers with roof span widths up to 125 feet are feasible for all conditions studied.
- The maximum compressive stress for any analysis made is 4,796 psi, which is approximately 50 to 60 percent of the average compressive strength of the dolomite.

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- Any tensile stresses can be controlled by standard methods of supporting rock;
- Excavation of chambers having an elliptical shape and excavation of an arched roof can remove rock tension zones, thereby minimizing the need for rock bolts.

No basic engineering problems associated with design and construction were identified in this study. However, the effects of local factors such as jointing and bedding must be considered in final siting and design studies.

A comparison of underground chambers constructed throughout the world indicates that large cavern sizes are not without precedent. Large chambers with roof spans up to 125 feet and heights of 125 feet have been constructed (table 26).

Table 26 Information on underground chambers constructed throughout the world.

Project	Date	Cavern size (ft) (l)	(w)	(h)	Depth (ft)	Rock types and conditions	Support details	Source
Cruachan, Scotland	-	300	77	125	-	Granite and dorite	Rock bolts: 15 ft long, 7.5 ft on center with concrete ribs	Hendron and Fernandez (1983)
Hongrin Switzerland	1970	450	100	90	-		Prestressed anchors and shotcrete	Hendron and Fernandez (1983)
Boundary Washington	1965	476	76	175	660	Good quality limestone and dolomite. RQD: good to excellent	Rock bolts: 15 ft long, 5 ft on center supplemented by 30 ft long bolts in arch; rock bolts as required in sidewalls	Hendron and Fernandez (1983)
Cavities I and II Rainer Mesa, Nevada	-	120	80	140	1300	Tuff. RQD: 95% to 100%	Arch: rock bolts 32 ft long, 3 ft on center; some gunite. Sidewalls: rock bolts 24 ft long, 6 ft on center	Cording et al. (1971)
Northfield Mountain, Massassachetts	1971	328	70	155	550	Interbedded gneiss, quartzite and mica schist. RQD: good to excellent (est.)	Arch: rock bolts 25 and 35 ft long 5 ft on center and 4 in. of mesh reinforced gunite. Sidewalls: 20 and 16 ft long rock bolts, 5 ft on center in upper part and as required in lower part of wall	Wild and McKittrick (1971)
Dupont Circle Station, Washington, D.C.	1973	720	76	44	70	Quartz mica schist. RQD: Fair to poor	Reinforced shotcrete lining in arch with 1 1/8 in. diameter, 20 to 24 ft rock bolts spaced 5 ft on center; welded wire reinforced shotcrete lining and 1 in. diameter 10 to 20 ft long, rock bolts 5 ft on center in walls	Cording, Mahar and Brierley (1977)

Table 26 Information on underground chambers constructed throughout the world—*continued*.

Project	Date	Cavern size (ft) (l)	(w)	(h)	Depth (ft)	Rock types and conditions	Support details	Source
Helms Project California	1982	336	83	126	1000	Grandiorite	Arch: Rock bolts 18 ft long and 6 ft on center and shotcrete. Side-walls: rock bolts 26 ft long and 10 ft on center	Strassburger (1981)
TARP Pumping Station Chicago, Illinois	-	274	63	96	350	Dolomite, dolo-mitic shale, and shale. RQD: 95% to 100%	Concrete-lined arch with 20 and 30 ft long, 1 3/8 in. diameter rock bolts spaced 4 ft on cen-ter and 2 in. of wire rein-forced shotcrete. Sidewalls: rock bolts 1 in. diameter, 10 ft long and 5 ft on cen-ter and 2 in. of shotcrete	Sylvester (1985)
Imaichi Nikko, Japan	1982	525	110	167	1312	Altered sandstone and slate brecca, siliceous sand-stone, hard and massive	Arch: 33 to 49 ft pre-stressed rock anchors 13 × 6.5 centers and 16 ft rock bolts 6.5 × 3.3 centers, w/12 in. shotcrete. Support pressure = 14 to 17 psi. Sidewalls: same rock anchors and bolts; bolt spacing 6.5 × 4 ft centers, w/6 to 9 in. shotcrete.	Mizukoshi and Mimaki (1985)
LEP CERN	1986	234	74	77	470	Limestone-marl, soft to hard conglomerate. RQD: 70% to 94%	Arch: 10 to 20 ft anchors, 6.5 × 6.5 ft, centers, 4 in. shotcrete. Sidewalls: 10 ft anchors, 4 in. shotcrete.	LEP project reports
Darquinah Algeria	1951	73	106	85	-	Poor rock	Fully concrete lined	Hendron and Fernandez (1983)
Nechako-Kemaro-Kitimat Canada	1965	1140	82	139	1000	Granite and granodiorite	Concrete arch and rock bolts	Hendron and Fernandez (1983)
Bathie France	1960	405	81	106	-	Mica schist	Concrete arch and columns with rock bolts and gunite	Hendron and Fernandez (1983)
Koyna India	1965	545	85	-	-	Highly laminated rock deterioration on exposure	Reinforced concrete lined in arch and walls	Hendron and Fernandez (1983)
Fadalto et Nove Italy	1970	227	102	187	-	Limestone	Concrete lined arch, walls fully supported	Hendron and Fernandez (1983)
Santa Massenza Italy	1953	650	95	92	-	Good quality limestone; high groundwater inflow	Concrete lined arch and walls	Hendron and Fernandez (1983)

Table 26   Information on underground chambers constructed throughout the world—*continued.*

Project	Date	Cavern size (ft) (l)	(w)	(h)	Depth (ft)	Rock types and conditions	Support details	Source
Somplago Italy	1957	292	82	114	-	Poor quality dolomite with clay-filled joints	Concrete lined arch with 10 ft long rock bolts 6.5 ft on center and 20 ft long bolts 8.0 ft on center in walls	Hendron and Fernandez (1983)
Kisenyana Japan	1967	200	83	165	810	Slate, sandy slate, and chert	Reinforced concrete arch with 16 to 50 ft long rock bolts 9 ft on center in sidewall	Cording et al. (1971)
Covergno Switzerland	1955	337	92	71	-	Mica schist. Foliation strike perpendicular to machine hall longitudinal axis	Concrete lined arch and walls	Hendron and Fernandez (1983)
Tumut 1 Snowy Mountains Australia	1958	300	77	110	1100	Biotite granite and granite. RQD: fair to good	Concrete lined arch with 15 ft long 1 in. diameter rock bolts 4 ft on center. Sidewalls: 12 ft long 1 in. diameter rock bolts	Cording et al. (1971)
Tumut 2 Snowy Mountains Australia	1962	320	60	110	750	Granite and granite gneiss	Concrete ribs 2 ft thick and 10 ft on center	Hendron and Fernandez (1983)
Churchill Falls, Canada	1970	1000	81	145	1000	Diorite and gneiss gneiss	Rock bolts: 1-1/8 in. diameter, 5 ft on center	Benson et al. (1971)
Outrades 3 Canada	-	-	76	250	500	Diorite	Rock bolts: 12 to 18 ft long, 6 ft on center	Hendron and Fernandez (1983)
Portage Mountain Canada	1965	890	67	144	200	Interbedded sandstone, shale, and coal measure rocks	Rock bolts: 14 to 20 ft long, 5 ft on center	Hendron and Fernandez (1983)
El Toro Chile	-	335	80	126	-	Granodiorite	Arch: Rock tendons 49 to 55 ft long, 20 ft on center; supplemented by 18 ft long rock bolts 8 ft on center. Sidewalls: Rock tendons 50 ft long, 20 ft on center	Cording et al. (1971)
Waldeck II Germany	-	344	110	164	-	Gneiss	Prestressed rock anchors and 7 to 10 in. thick shotcrete lining	Hendron and Fernandez (1983)
Ferrera Switzerland	1962	469	95	82	492-984	Gneiss	Permanent support: concrete vault, unreinforced	Gysel (1986)
Kuinco Peru	1965	354	102	79	1640	Massive crystalline	Permanent support: concrete vault, unreinforced	Gysel (1986)
Porabka Zar Poland	1976	407	86	131	492	Schist of siltstone, mudstones, and limestone		Gysel (1986)

Table 26   Information on underground chambers constructed throughout the world—*continued.*

Project	Date	Cavern size (ft) (l)	(w)	(h)	Depth (ft)	Rock types and conditions	Support details	Source
El Cajon Honduras	1985	341	97	139	328-656	Karst limestone	Arch: concrete. Sidewall: rock bolts and shotcrete	Gysel (1986)
Middle East	1986	274	75	135	1148	Limestone	Arch and sidewalls: concrete	Gysel (1986)
Le Sautet France	1933	115	115	66	328			Duffaut (1986)
La Bathie France	1959	407	82	106	-	Granite		Duffaut (1986)
Mostezic France	1978	-	82	138	984			Duffaut (1986)
Tai Koo Hong Kong	1986	82	79	53	65-262	Granite	Arch: 10 to 30 ft bolts on 5 ft grid and 4 in. shotcrete. Sidewall: 10 to 23 ft bolts, 1 in. diameter, 2 to 4 in. shotcrete	Sharp et al. (1986)
Huvudsta Sweden	1982	-	69	16	23	Granite, RMR 70-35	Bolts and 4 in. shotcrete	Stille (1986)
Defense Sweden	1984	-	98	43	-	Gneiss, RMR 64	8.5 ft bolts, 7.3 ft grid	Stille (1986)
Holmlia Norway	-	148	82	43	65	Gneiss	5 to 15 ft rockbolts w/ 2 to 4 in. shotcrete	Rygh (1986)
Kaunianen Finland	-	146	94	36	-	Gneiss	13 to 16 ft on 5 ft spacing; 4 in. shotcrete roof, 2 in. shotcrete sidewall	Roininen (1986)
Cirata Java, Indonesia	-	830	115	162	-	Tuff, RMR 55-72, shear zones, RMR = 18-28, Qu = 4,000 psi	Arch: 23 ft bolts, 49 ft anchors and shotcrete. Sidewalls: 16 ft bolts, 65 ft anchors	Reik et al. (1986)
Chaira	-	364	74	141	1115	Granite	40 to 65 ft cables, 10.5 to 13 ft grid, 15 ft short anchors, 5.5 ft grid w/ 6 to 8 in. shotcrete	Kaluchew (1986)
Nation Station France	-	738	82	36	53	Soft rocks	Concrete segments	Duffaut (1986)
Liujiaxia China	1960s	282	102	210		Mica schist	16 to 20 ft, 1.75 in. diameter grouted rock-bolts; concrete arch	Zongliang (1986)
Baishan China	-	-	82	178	-	Qu = 11,000 to 18,000 psi	11.5 to 13 ft rockbolts, w/ shotcrete and	Zongliang (1986)
Longyangxia China	-	-	125	125	-			Zongliang (1986)

Table 27 In situ stress conditions and expected tangential stresses at tunnel crown and springline for a tunnel in the SSC study area. (Note: negative tangential stress indicates tension.)

Rock unit	Depth range (ft)	σ_1 / σ_v	σ_2 / σ_v	UCS (psi)	Tensile strength (psi)	Tunnel perpendicular to σ_1 direction tangential stress			Tunnel perpendicular to σ_2 direction tangential stress		
						Crown (psi)	Spring (psi)	UCS/ σ_1	Crown (psi)	Spring (psi)	UCS/ σ_2
Silurian	75-200	5	3	16,065	1,159	2,800	-400	16	1,600	0	26
Galena Wise Lake	350-450	3-5	2	10,034	1,089	6,300	-900	4.5	2,250	+450	11
Dunleith	350-450	3-4	2	7,600	635	4,950	-450	4.2	2,250	+450	8
Platteville	400-600	3	1	12,169	1,411	4,800	0	6.7	1,200	+1,200	20

Ground Behavior

Geotechnical data and tunneling experience in the area indicate that the ground reaction to excavation of large chambers and tunnels in the dolomites is loosening along bedding and joints (loosening ground conditions). This conclusion is based on the joint spacing (which is wide with respect to the size of the openings) and on in situ stresses measured in the dolomites. These stresses show that the maximum principal stress (σ_1 or σ_H) is horizontal, oriented N55-65°E, with ratios of σ_H/σ_v ranging from 3 to 5 depending on the bedrock unit (Haimson 1987). The intermediate principal stress (σ_2 or σ_h) is also horizontal, oriented N25-35°W, with ratios of σ_h/σ_v ranging from 1 to 3 depending on the rock units.

The ratios of rock strength (unconfined compressive strength) to in situ stress, or of rock strength to tangential stress, are good indicators of potential rock instability problems within the excavated tunnels. Tangential stress is the stress at the skin of the circular opening of the tunnel. Stresses are concentrated around the opening because they have to support the additional loads produced by creating the opening. In situ rock stresses and expected tangential stresses at tunnel crown and springline for a tunnel axis perpendicular to the σ_1 and σ_2 directions respectively are summarized in table 27. For a tunnel perpendicular to the σ_2 direction, these ratios are sufficiently high to indicate that no rock stress problems exist. The same conclusion can be made for tunnels in the Silurian and Platteville, where tunnels are perpendicular to the σ_1 direction. At depths of 450 feet in the Wise Lake and Dunleith dolomites the ratios are low enough to indicate the possibility of mild stress slabbing. This condition can be routinely handled by spot bolting. Calculated ratios of rock strength to tangential stress for deeper conditions produce the ranges of 3 to 5, which is moderate slabbing, and 1 to 3, which is heavy slabbing.

Advance Rates

Estimates of advance rates for the tunnel boring machines (TBM) can be made by examining excavation rates achieved on other rock tunneling projects in the region or by utilizing empirical relations based on material properties and measured TBM advance rates.

Field penetration indices, defined as the ratio of the average thrust per cutter to the penetration rate (Nelson et al. 1983), were determined for the Silurian (85 to 103 kips/inch), Maquoketa (50 kips/inch), and the Galena and Platteville (65.5 to 72.2 kips/inch).

Estimates of instantaneous advance rates for a tunnel can be made empirically by using the average rock values summarized on table 14 and other laboratory test data (Nelson et al. 1983,

Tarkoy 1975). Such estimates are dependent on the rotating speed (rpm) of the TBM cutterheads and the thrust characteristics of the TBM.

For the Silurian, Maquoketa, and Galena/Platteville respectively, overall penetration rates, determined on the basis of the relationship between the Taber abrasion hardness and penetration rates found by Nelson et al. (1983), were 0.33, 0.40, and 0.37 inches per revolution of a TBM cutterhead.

Conservative estimates of a penetration rate of 0.3 inches/revolution, machine rpm of 15 (which equals 500 ft/min outside cutter speed), machine utilization 40 percent (Nelson et al. 1985), and two shifts per day (two 10-hr shifts), indicate that an average advance rate of 180 feet per day would be possible in the Galena and Platteville. These data utilize results of testing by the Robbins Company on Galena and Platteville samples from northeastern Illinois. One TBM machine used on TARP recently set another driving record. The world's largest hard-rock machine—35.3 feet in diameter—drove 69 feet in one shift and 160 feet in 24 hours in the Silurian dolomite (ENR 1990).

The Robbins Company's report further states that the nonabrasive characteristics of the dolomite rock should result in very little cutter usage. Estimated cutter costs in the hardest dolomite rocks should not exceed $1.50/yd^3, and in most dolomite rocks the cost would be below $1.00/yd^3. Estimated cutter costs in the Maquoketa are substantially lower: about $0.30 to $0.75/yd^3 (in 1986 dollars).

UNDERGROUND CONSTRUCTION IN NORTHERN ILLINOIS AND MILWAUKEE

Previous Tunneling Experiences in Northeastern Illinois

The following information was obtained from previous tunneling experiences in northeastern Illinois, and also in Milwaukee, where construction conditions are similar to those in Illinois.

TARP caverns   Four large underground pumping caverns were excavated for TARP. The two TARP mainstream system pump house caverns are the largest and deepest excavated caverns in northeastern Illinois. The upper part of these caverns was mined in Silurian dolomite, the lower part in Maquoketa shale. The caverns, rectangular in plan, with rounded ends, are 310 feet long, 96 feet high, 63 feet wide, and 358 feet below the ground. They are oriented north-south to bisect the regional joint pattern. Design studies indicate that the arched crown support consisted of radial, fully grouted, tensioned rockbolts 1.375 inches in diameter by 30 feet long, and 4 feet on center each way. Rockbolt lengths were reduced to 20 feet because of the better-than-anticipated rock behavior observed in a 12×20-foot exploratory drift along the length of the cavern crown. During excavation of the crown the rock had a tendency to break along horizontal bedding planes and create slabs 6 to 12 inches thick. The rock slabbing created local support needs but did not affect overall stability of the opening. Further support was provided by a minimum 4-inch-thick layer of shotcrete reinforced with welded wire fabric. A nominal concrete roof arch 8 inches thick further assured long-term stability.

The sidewall support design consisted of rockbolt 1 inch in diameter by 10 feet long, angled 10° down on 5×5-foot centers. These were to be covered by a minimum 4-inch-thick layer of shotcrete reinforced with welded wire fabric. During construction the sidewall support in the upper 47 feet was changed to a pattern of anchor bars (no prestressing) 1.375 inches in diameter, 10 feet long, on 5×5-foot centers. Rockbolts were installed as designed in the lower 30 feet. Sidewall shotcrete was reduced to 2 inches and the reinforcement was deleted. No stress slabbing was observed in the caverns.

One of these caverns was excavated in 5 months, the other in 7 months; all supports and a formed concrete arch for each cavern were also completed during this time frame. The caverns are in McCook, Illinois, about 4 miles west of Midway Airport; public tours of the facilities are available. Two additional, slightly smaller caverns were excavated for TARP near Calumet. A brief description of these caverns and their ground conditions is found in Shuri and Kelsay (1984).

Additional experiences with the TARP work in Chicago are described in Dalton (1979), Kenny (1979), Martin (1979), Mixon and Kennedy (1979), Paschen (1979), and Weiss-Malik and Kuhn (1979).

Gas storage cavern In the early 1950s a liquid propane gas storage facility was excavated in the Maquoketa shale at a depth of about 260 feet near Eola, Illinois (near Aurora). The 50,000 barrel storage facility was abandoned and sealed in the early 1970s. It consisted of caverns 25 feet high and 10 feet across at the floor and 15 feet across at the roof; the walls sloped. A very general description is given in Bell (1956). Unpublished letter reports stated that some of the same ground-control problems were encountered at Eola as were encountered in a similar facility in the Maquoketa shale in Kankakee, Illinois. At the Kankakee site, according to Bell (1956), "spalling of the shale caused considerable difficulty during mining. In attempting to control the spalling, unsuccessful experiments were made with several types of coating materials (tried gunite and an asphaltic coating). The best solution was found to be roof bolting in conjunction with timbers which completely covered the ceiling area. The cavern walls were covered with strong wire mesh held in place by side bolts driven into the shale."

Undergound Construction in Milwaukee

Tunneling and underground construction is nearly as extensive in Milwaukee, Wisconsin, as in the Chicago area. Both cities are situated on very similar geologic materials—glacial material over Silurian bedrock. The geotechnical experiences of one city are therefore relevant to the other city. Meinholz and Wieland (1979) compiled a history of the previous 65 years of tunneling (including shaft construction, mixed face, and rock tunneling) in Milwaukee.

In 1977, the Milwaukee Water Pollution Abatement Program was started in response to the Federal Clean Water Act and court judgments. This program, similar to Chicago's TARP, includes about 20 miles of large-diameter rock tunnels. Meinholz and Santacroce (1987) present an overview of the entire program. Santacroce and Meinholz (1987) give a synopsis of tunnel boring machine experience, index and engineering properties of the rock, and shaft construction. Coon et al. (1987) provide information on water control, Ramage et al. (1989) on water inflow into the tunnels, and Shuster and Sopko (1989) on shaft construction. Budd and Cooney (1989), Doig (1989), and Mixon et al. (1989) describe soft ground tunneling experiences in the area, using two case histories.

DISCUSSION AND CONCLUSIONS

The nearly flat-lying Silurian and Ordovician rocks below the glacial deposits in northeastern Illinois have very desirable and predictable properties for the construction of large-diameter tunnels and large caverns. Tunnels as large as 35.3 feet in diameter and caverns 310 feet long, 96 feet high, and 63 feet wide have been constructed in the Silurian dolomite in the Chicago area. All have proved to be stable, and all require very limited support because of the good to excellent rock mass conditions. Sensitivity analysis has shown that caverns with much larger roof spans could be built in the dolomites.

The glacial deposits are less continuous than the bedrock deposits in the area, and their properties are less predictable. However, knowledge of the characteristics and distribution of the glacial deposits, along with construction experience, provide confidence in predicting the conditions that may be encountered in the area.

The final design of any underground structure requires site-specific investigations. Exploratory drifts are usually used during construction of large underground structures to provide data for assessing and measuring ground behavior at the structure location. Instrumentation is usually installed to monitor ground behavior of large structures during construction so that adjustments can be made in the ground support procedures to stop any problems that might arise.

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APPENDIX A TARP Data from Harza Engineering Company: Strength Properties for Formations of Northeastern Illinois

A-1 Strength properties of the Racine Formation (Silurian System, Niagaran Series)
A-2 Strength properties of the Romeo Member of the Joliet Formation (Silurian System, Niagaran Series)
A-3 Strength properties of the Margraf Member of the Joliet Formation (Silurian System, Niagaran Series)
A-4 Strength properties of the Elwood Formation (Silurian System, Alexandrian Series)
A-5 Strength properties of the Kankakee Formation (Silurian System, Alexandrian Series)
A-6 Strength properties of the Wise Lake and Dunleith Formations (Ordovician System, Galena Group)
A-7 Strength properties of the Platteville Group (Ordovician System)

APPENDIX B ISGS Geotechnical Data for the SSC Study Area

B-1 Silurian bedrock samples
B-2 Maquoketa Group (Ordovician) dolomitic shale and shale samples
B-3 Maquoketa Group (Ordovician) dolomite samples
B-4 Maquoketa Group (Ordovician) limestone samples
B-5 Samples from the Wise Lake Formation (Ordovician, Galena Group)
B-6 Samples from the Dunleith Formation (Ordovician, Galena Group)
B-7 Dolomite samples from the Platteville Group (Ordovician)
B-8 Samples from the St. Peter Sandstone (Ordovician, Ancell Group)

TABLE A-1 Strength properties of the Racine Formation (Silurian System, Niagaran Series) in northeastern Illinois (TARP data from Harza Engineering 1975b).

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
74-4	15	93.4	81.4	8,550				
				12,640				
74-5	17	99.3	90.5	7,620				9.24
74-7	17	95.4	89.3	7,570				
				10,410				
74-9	22	98.6	92.7	3,830				
				5,830				10.45
				7,320				
				11,950				13.71
74-12	14	99.6	98.2	3,120				
74-16	18	99.8	91.7	8,558				
74-17	15	98.3	88.7	3,230				
				8,030				10.66
74-18	14	100.0	82.2	6,060				
74-19	15	100.0	92.4	5,060				6.66
74-24	21	99.8	95.7	5,200				7.89
				4,540				
				2,530				
74-26	17	99.8	96.5	6,510				8.39
				10,410				
74-29	11	99.8	94.9	7,290				
				9,320				
74-30	11	99.6	93.5	8,960				
74-31	10	100.0	93.0	3,950				
74-32	11	99.5	92.5	13,490				
74-33	10	94.8	86.6	10,560				
74-34	12	91.7	83.0	6,050				
74-35	14	96.7	92.1	11,410				
				10,330				11.20
				14,720				
				11,900				
74-38	13	98.7	93.5	6,200				
74-39	11	97.1	88.8	12,530				
74-43	10	99.5	94.4	5,280				
74-45	10	96.7	93.1	4,240				
71-1(52)	15	95.1	78.9	7,400	1,200	5.1	2.77	
				7,290		2.5	2.77	
				16,800	1,380	1.4	2.78	
				18,290		0.9	2.79	9.05
				7,350	1,290	1.2	2.79	
71-2(39)	13	91.4	88.0	24,230		1.1	2.82	12.10
				7,970	650	1.1	2.76	
				7,350		3.4	2.80	
				3,000	1,040	6.9	2.75	
71-3(35)	9	92.8	86.4	3,280	1,280	8.3	2.82	
					1,040	4.3	2.87	
71-4(37)	8	97.7	86.1	19,510		3.6	2.69	
				7,550	1,870	4.9	2.74	
				9,020		3.6	2.86	
71-5(40)	12	98.0	80.6	17,820		0.6	2.81	
				12,020	190	2.8	2.78	
				8,840		1.6	2.72	
71-6(41)	12	99.1	92.1	10,680		1.2	2.80	
				10,680	1,200	0.5	2.78	
71-7(28)	11	99.5	96.9	4,730	1,140	2.9	2.77	
				10,070		1.0	2.77	
				8,510	1,100	1.9	2.76	
				10,070		2.5	2.76	10.69
71-8(76)	13	99.4	96.1	24,450		1.1	2.79	
				12,250	1,190	2.5	2.78	
				14,400		3.1	2.85	7.15
				10,790	1,190	1.8	2.80	
71-9(31)	6	95.8	87.5	1,770	700	6.8	2.73	
				8,530		3.3	2.78	
71-10(45)	14	97.6	94.1	14,910		0.4	2.73	
				16,880	1,220	0.8	2.74	
				6,840		1.0	2.77	
				10,480	1,050	2.1	2.80	8.50

TABLE A-1   (continued)

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-11(38)	7	96.9	68.1	13,360		5.4	2.82	
				3,680	1,290	4.3	2.73	
71-12(42)	13	98.1	83.5	8,390	1,860	4.5	2.84	
				11,970		2.7	2.86	
				8,100	1,670	3.0	2.84	
				9,390		3.2	2.85	9.15
71-13(72)	15	98.7	86.7	9,865	1,070	4.5	2.75	
				10,310		4.1	2.80	
				15,830		2.0	2.83	
71-14(34)	7	85.7	62.0	8,470		1.3	2.76	
				4,230	1,480	0.7	2.77	
71-15(36)	7	97.2	86.2	7,250		0.7	2.78	
				8,540	1,010	4.4	2.69	
71-16(43)	10	97.3	91.5	6,630		4.2	2.83	
				3,570		3.3	2.82	
				19,440		1.5	2.81	
				9,350	1,910	2.0	2.72	
71-17(69)	19	97.9	88.3	4,710		4.0	2.79	
				11,860		2.3	2.77	
				10,090		7.0	2.72	
				7,730		2.7	2.75	
				8,250		1.8	2.77	
71-18(44)	16	99.0	86.1	12,520		0.9	2.81	
				4,790	2,240	1.1	2.79	
				7,550		2.5	2.73	
				9,930	1,520	2.2	2.78	
71-19(70)	16	97.0	88.4	9,020	1,060	3.5	2.78	
				5,520		5.6	2.85	
				5,710	1,480	0.1	2.57	
				5,340		6.2	2.80	8.27
				4,790	1,290	3.3	2.86	
				13,260		3.4	2.86	
71-20(49)	14	94.6	68.2	6,200		5.0	2.79	
				13,810		3.5	2.83	
				13,990	1,750	1.7	2.78	
				5,890		4.5	2.78	6.53
				13,620	1,520	3.4	2.84	
71-21(51)	16	96.3	69.7	8,980		1.9	2.81	
				6,040	1,410	3.4	2.81	
				19,440		2.9	2.88	
				41,970	1,890	0.8	2.79	10.55
71-22(71)	15	98.2	87.9	5,230	1,370	4.2	2.84	
				15,830		2.5	2.77	
				19,050	2,040	1.7	2.82	
71-23(6)	3	94.3	52.7	6,630	1,710	1.5	2.67	
71-24(47)	13	96.5	82.7	14,210	1,010	1.7	2.86	
				8,910		3.0	2.75	
				8,910	1,360	4.3	2.84	
71-25(62)	14	98.4	62.1	15,700	1,260	2.7	2.81	
				12,080		2.9	2.75	
71-27(33)	9	98.6	76.4	5,520		0.3	2.80	
				5,150		6.7	2.91	
71-28(10)	5	91.0	73.8	14,360		3.3	2.74	
71-29(73)	11	96.5	80.6	5,600	780	2.8	2.75	
				6,260		3.7	2.74	
				10,770	1,550	1.7	2.81	
				14,030		1.7	2.80	11.40
71-30(75)	12	98.3	91.8	9,500	1,190	0.1	2.72	
				16,220		0.1	2.75	
				5,080	1,580	0.5	2.75	
				15,460		0.2	2.79	9.80
71-31(61)	15	99.1	76.1	9,570		1.2	2.81	
				5,880	1,560	3.2	2.72	
				7,920		3.3	2.78	
71-32(79)	15	98.8	86.4	9,470		6.7	2.86	5.40
				9,020	1,770	3.1	2.90	
71-33(30)	8	98.8	77.6	4,690				
	7			2,760		0.4	2.77	8.27

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-34(81)	12	97.5	85.7	28,050		0.4	2.82	
				18,220		1.6	2.79	
				9,110	1,440	0.8	2.76	6.16
71-35(60)	16	98.2	85.0	4,420		5.0	2.79	4.49
				3,000		1.8	2.78	
71-36(80)	15	97.5	88.3	20,990		3.4	2.80	
				7,820	2,100	5.2	2.82	11.21
				22,830		2.3	2.83	
				14,890		2.9	2.84	
71-37(32)	9	98.0	69.7	4,230		2.3	2.66	
				5,890	590	2.1	2.68	7.14
				20,250		1.8	2.72	
71-38(78)	14	99.3	90.0	10,130	2,370	0.7	2.77	7.18
					3,030	0.8	2.82	
71-39(82)	12	99.1	91.8	21,360		2.0	2.76	
				11,780		2.6	2.77	
				9,390	1,520	3.2	2.76	5.91
				11,230				
71-40(63)	10	98.0	77.3	5,160	1,970	2.4	2.78	6.32
71-41(74)	10	99.2	95.4	8,840	1,890	0.9	2.73	10.08
				11,050		0.9	2.80	
71-43(77)	14	98.8	92.2	9,450		1.5	2.82	8.49
				12,230	1,630	0.9	2.82	
				13,970	2,710	0.4	2.79	
71-44(29)	10	94.3	79.2	9,210	930	4.3	2.76	4.24
				3,420		4.8	2.81	
71-46(48)	14	97.4	84.8	3,610		3.8	2.80	6.92
				12,520	1,020	3.7	2.79	
				10,130	1,450	1.6	2.82	
71-47(23)	6	97.6	66.2	11,780	2,710	1.0	2.73	10.31
71-48(50)	14	97.7	86.4	13,260		0.5	2.77	
				8,840	940	0.1	2.58	
				5,340				
				8,980	920	0.7	2.75	9.40
71-49(53)	16	88.0	30.6	9,210		4.4	2.89	8.50
71-50(12)	6	98.8	73.4	5,710	1,410	5.5	2.74	
71-51(25)	7	94.9	54.7	27,980		2.2	2.78	
				7,360		3.4	2.79	6.86
71-52(46)	16	96.8	64.6	6,810		5.3	2.80	
				10,390	1,860	4.2	2.82	
				6,550	1,760	4.1	2.81	8.12
71-53(58)	17	98.1	76.6	4,490	1,440	6.0	2.79	5.86
71-54(13)	8	99.5	81.6	16,940		4.2	2.75	
				20,250	1,530	2.2	2.78	10.79
71-56(Q-1)	19	95.2	67.9	5,160	1,270	1.9	2.81	
				5,770		2.6	2.80	
				11,050				6.46
71-57(54)	14	98.9	89.4	4,590		3.1	2.80	5.55
				6,990		3.9	2.80	
				12,950			2.82	
71-58(19)	10	99.0	82.0	8,100	1,010	2.8	2.77	3.97
71-59(57)	14	97.9	73.7	7,550	2,220	2.8	2.80	7.92
71-60(Q-2)	19	99.1	83.1	8,200	1,700	2.7	2.78	
71-61(20)	14	99.0	78.4	7,630	1,560	8.4	2.73	
71-62(59)	18	98.2	77.9	5,160		1.9		
				5,390		5.8		
				6,700	1,860	3.8		
71-63(89)	17	98.0	70.2	10,200	1,760	3.6	2.76	
71-64(56)	17	89.4	73.9	5,890		1.9	2.80	
71-65(F-9)	2	79.0	41.0	6,580		5.0	2.78	
71-66(1)	6	99.0	90.8	8,470	2,250	2.5	2.81	11.29
71-69(5)	6	91.7	70.7	10,860		3.2	2.81	
71-70(14)	9	98.2	86.0	10,310	1,590	6.3	2.74	
				9,110		3.2	2.77	
71-72(18)	10	98.2	77.2	18,700		2.2	2.79	
71-73(15)	9	95.1	86.6	7,180	1,070	5.5	2.72	
71-74(3)	4	98.0	85.0		1,470	0.6	2.79	
71-75(17)	10	98.8	86.4	7,920		1.9	2.82	

TABLE A-1   (continued)

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-77(F-4)	15	99.5	85.1	8,190	3,210	0.8	2.81	
71-78(F-8)	4	99.3	89.8	7,100		3.6	2.82	
71-80(F-1)	8	99.4	90.6	9,940	1,520	2.8	2.79	
71-81(F-2)	8	99.3	86.4	11,110		1.5	2.82	
71-82(96)	6	95.7	72.3	17,670		1.6	2.79	
71-83(87)	17	98.8	57.1	6,700	2,340	8.2	2.70	
71-87(F-7)	13	98.2	70.9	8,100		3.4	2.82	
				15,460	2,220	2.1	2.82	
71-88(53B)	13	98.5	87.0	7,000	1,810	2.9	2.84	7.89
71-89(55)	13	99.7	74.1	7,360		3.7	2.84	
				7,650		3.7	2.82	
71-90(53A)	15	96.3	79.1	15,460	1,740	2.2	2.82	
71-91(67)	17	98.7	80.7	4,690	2,010	3.5	2.84	
71-92(65)	17	98.9	80.8	15,110	1,340	2.2	2.83	
71-95(88)	17	94.1	71.8	7,360		4.4	2.84	
				12,620	2,240	2.2	2.82	
				7,650		2.2	2.82	
71-96(88)	20	98.9	64.2	3,390	1,220	4.5	2.79	
				21,480		1.6	2.83	
71-97(Q-3)	18	98.7	74.8	6,700	1,630	2.0	2.86	
				10,380		2.7	2.80	
				6,260	1,500	3.2	2.86	
				12,380		2.5	2.82	
				9,200	2,060	1.7	2.85	
Average		97.5	82.2	9,861	1,535	2.8	2.79	8.36
Maximum				41,970	3,210	8.4	2.91	13.71
Minimum				1,770	190	0.1	2.57	3.97

TABLE A-2   Strength properties of the Romeo Member of the Joliet Formation (Silurian System, Niagaran Series) in northeastern Illinois (TARP data from Harza Engineering 1975b).

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
74-4	2	98.0	95.5	12,830				
74-5	2	100.0	99.0	13,940				12.44
74-12	2	100.0	100.0	7,360				7.00
74-16	2	100.0	99.0	20,630				15.20
				13,940				12.40
74-18	2	100.0	94.5	11,600				10.80
74-19	2	100.0	94.0	4,980				
74-21	2	100.0	100.0	13,610				12.50
74-24	2	100.0	100.0	7,430				7.56
74-27	2	100.0	95.5	7,430				11.54
				14,310				
74-28	2	100.0	97.0	13,570				
74-29	2	100.0	100.0	15,410				
74-30	2	100.0	100.0	19,590				
74-31	2	100.0	99.0	13,120				14.86
74-32	2	100.0	100.0	15,690				
74-33	2	96.0	92.5	6,990				
74-36	2	100.0	96.5	10,860				
				13,830				9.48
74-38	2	100.0	100.0	7,330				10.10
74-38	2	100.0	100.0	16,880				
74-45	2	100.0	100.0	8,700				
71-1(52)	1	100.0	95.0	37,390		0.5	2.82	
71-3(35)	2	100.0	85.0	11,660	1,600	9.7	2.47	7.15
71-4(37)	1	100.0	100.0	15,830		2.8	2.85	
71-6(41)	1	100.0	100.0		2,140	0.5	2.81	
71-7(28)	1	100.0	100.0		2,190	0.3	2.82	
71-8(76)	1	100.0	96.0	32,030	3,380	0.9	2.82	
71-9(31)	2	85.0	79.0	18,490	2,360	0.3	2.78	
71-11(38)	1	100.0	94.0	12,520		3.2	2.84	
71-13(72)	1	98.0	96.0	25,770		1.5	2.83	9.43
71-17(69)	2	98.0	96.0	29,460		1.9	2.82	9.81
71-22(71)	1	98.0	92.0	10,680		3.0	2.78	10.60
71-24(47)	1	100.0	74.0	11,640		2.6	2.69	
71-27(33)	1	100.0	82.0	31,100		0.4	2.77	9.56
71-28(10)	1	98.0	91.0	26,330	2,510	1.3	2.86	
71-30(75)	1	99.0	95.0	8,540	2,530	1.9	2.82	
71-31(61)	1	99.0	97.0	23,640	1,940	1.1	2.82	23.60
71-36(80)	1	99.0	96.0		3,420	0.4	2.83	
71-41(74)	2	99.5	97.5	37,930	2,420	0.2	2.80	10.72
71-46(48)	1	99.0	96.0	23,320				
71-50(12)	2	100.0	85.0	26,330		0.9	2.80	14.11
71-55(F-10)	1	94.0	80.0	31,690		0.9	2.79	9.83
71-60-(Q-2)	1	100.0	96.0	20,760		1.8	2.80	
71-71(2)	1	100.0	90.0	15,100		0.2	2.76	14.31
71-82(96)	1	99.0	88.0	7,360		4.8	2.81	
71-83(87)	1	100.0	90.0	28,870		1.3	2.77	
71-85(95)	1	100.0	90.0	10,670	3,120	1.7	2.81	
71-89(55)	2	96.5	94.5	19,310	3,000	1.3	2.83	16.30
71-91(67)	2	99.5	92.0	28,350	2,890	1.2	2.82	
71-92(65)	2	100.0	96.5	11,650	3,150	1.0	2.85	
Average		99.0	94.9	17,218	2,618	1.7	2.80	11.79
Maximum				37,930	3,420	9.7	2.86	23.60
Minimum				4,980	1,600	0.2	2.47	7.00

TABLE A-3   Strength properties of the Margraf Member of the Joliet Formation (Silurian System, Niagaran Series) in northeastern Illinois (TARP data from Harza Engineering 1975b).

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
74-4	3	98.3	96.3	12,080				
				10,410				
74-5	2	100.0	100.0	9,480				
74-7	2	99.5	99.0	13,010				13.50
74-9	3	94.0	85.7	6,690				
74-12	2	100.0	100.0	7,660				6.65
74-19	2	100.0	97.0	6,100				6.05
74-26	2	100.0	97.0	6,320				8.13
74-28	2	100.0	100.0	16,170				
				14,500				
74-29	3	100.0	100.0	12,180				9.61
74-30	3	100.0	99.3	15,320				10.80
74-32	2	100.0	100.0	7,060				6.36
74-34	3	100.0	91.7	13,390				14.60
74-35	3	99.7	99.3	13,230				
				7,730				10.00
74-43	3	100.0	99.3	14,940				10.34
74-44	3	100.0	97.7	5,720				
74-45	2	100.0	97.5	8,550				8.07
71-1(52)	3	99.3	98.7	20,010		0.8	2.79	
71-2(39)	4	99.0	96.5	22,220	1,910	0.6	2.76	
71-3(35)	3	96.0	82.3	12,390	1,640	1.7	2.86	
71-4(37)	4	96.3	91.3	9,020	1,870	1.4	2.82	
71-5(40)	4	98.8	96.5	14,910	1,410	0.4	2.82	7.73
				10,090		0.6	2.83	
71-6(41)	3	100.0	99.3	15,710		0.8	2.86	
71-7(28)	4	99.0	96.0	25,580	1,460	1.4	2.82	
71-8(76)	2	100.0	98.5		2,250			
71-10(45)	3	100.0	97.0	24,520		0.6	2.84	
71-11(38)	4	99.0	97.5	18,410	2,540	1.0	2.87	8.25
71-12(42)	5	98.4	93.4	8,470	1,560	3.7	2.84	
				10,310		1.2	2.83	
71-14(34)	5	98.8	91.2	16,750		0.5	2.78	
				20,070	1,600	1.0	2.80	7.24
71-15(36)	4	98.8	95.5	13,770		13.9	2.64	
				15,830	1,820	1.4	2.81	7.02
71-16(43)	3	99.0	95.3	16,200		2.5	2.83	9.47
71-17(69)	2	99.5	97.5	16,940		2.1	2.84	6.58
71-18(44)	4	99.5	99.0	14,730		1.8	2.85	6.72
71-19(70)	2	98.5	95.0	17,310	1,950	2.6	2.85	
71-20(49)	2	98.5	95.0	22,090		3.1	2.81	
71-21(51)	2	98.5	95.5	21,310		0.3	2.80	
71-23(6)	4	98.8	83.8	13,770		0.7	2.83	
71-24(47)	4	99.3	96.0	15,720	2,490	3.9	2.88	8.98
71-25(62)	3	99.0	95.0	19,510	1,070	0.8	2.82	
71-27(33)	3	98.7	97.3	4,930	2,230	0.4	2.82	
71-29(73)	3	99.0	94.3	18,780	1,660	1.0	2.81	
71-30(75)	1	99.0	95.0	8,540	2,530	1.9	2.82	
71-32(79)	2	100.0	99.0	23,500	2,510	2.4	2.81	6.32
71-33(30)	4	100.0	94.5	20,990		1.1	2.76	
71-34(81)	3	98.7	92.3	9,110		0.8	2.81	5.37
71-35(60)	3	99.3	96.0	15,670	2,060	1.2	2.79	
71-36(80)	2	99.5	94.5	21,360		1.1	2.81	5.28
71-37(32)	4	97.3	91.3	11,230	1,990	3.1	2.76	
71-39(82)	3	99.3	96.7	16,200	1,790	1.6	2.77	
71-40(63)	3	98.3	96.3	16,940		1.3	2.79	4.28
71-42(27)	4	99.0	97.0	12,990		3.2	2.80	
71-43(77)	3	99.0	97.0	23,840				
71-44(29)	4	98.5	93.5	18,960		1.4	2.78	
71-45(21)	3	99.0	89.7	24,670		1.2		8.10
71-46(48)	2	98.5	93.5	20,780		1.3	2.81	14.50
71-48(50)	2	96.0	90.5		1,440	1.5	2.81	7.57
71-50(12)	4	97.8	80.8	22,280		1.1	2.75	7.30
71-51(25)	4	98.3	91.8	20,620		1.6	2.78	
71-52(46)	3	99.7	94.3	16,570		3.1	2.79	
71-54(13)	4	98.8	90.5	17,670		3.8	2.73	6.93
71-57(54)	3	99.0	94.0	21,170		2.0	2.79	6.26

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-58(19)	4	99.3	94.0	18,230		3.5	2.75	6.00
71-65(F-9)	4	98.3	87.3	17,060		0.9	2.79	
71-68(9)	4	99.0	89.0	22,690		2.8	2.78	
71-70(14)	4	99.5	95.5	9,470		4.8	2.81	
71-71(2)	4	98.5	93.0	10,680	2,020	0.9	2.80	
71-72(18)	4	98.5	84.3	10,490	1,860	1.9	2.80	
71-74(3)	4	98.5	93.0	9,020		2.3	2.76	
71-75(17)	4	98.5	91.0	11,050		0.5	2.72	
71-76(8)	4	99.0	91.5	18,940		1.7	2.79	
71-77(F-4)	3	98.0	93.0	12,750		1.3	2.81	
71-81(F-2)	3	100.0	91.0	11,110	1,970	5.1	2.76	
71-95(88)	2	100.0	92.0	14,540	2,490	1.9	2.82	
71-97(Q-3)	3	100.0	93.0	14,560	2,630	1.6	2.82	
				4,510	1,890	1.7	2.83	
Average		98.9	94.0	14,918	1,952	1.8	2.71	8.13
Maximum				24,670	2,630	13.9	2.88	14.50
Minimum				4,510	1,070	0.3	2.64	4.28

TABLE A-4 Strength properties of the Elwood Formation (Silurian System, Alexandrian Series) in northeastern Illinois (TARP data from Harza Engineering 1975b).

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
74-4	5	95.6	87.2	5,390				
74-7	7	97.7	96.6	13,570				
74-18	10	100.0	96.2	4,140				
				14,910				14.88
74-19	7	100.0	97.3	5,800				
				4,200				
74-21	11	100.0	100.0	6,020				
74-26	9	100.0	97.8	2,490				
74-27	2	100.0	99.0	8,360				
74-28	3	99.7	99.0	10,220				8.90
74-32	2	100.0	97.5	8,180				10.90
74-33	4	98.8	95.5	9,670				13.45
				12,940				13.64
				13,610				
74-34	6	100.0	83.7	14,200				
74-36	10	100.0	88.5	7,290				
74-38	10	98.8	97.0	13,080				
				6,770				
				7,440				7.32
74-39	10	97.8	93.8	10,110				7.50
				9,290				7.25
				7,060				
74-41	10	100.0	94.0	6,910				
74-44	10	99.9	98.3	10,780				
71-1(52)	9	97.7	96.2	14,590	1,070	0.9	2.78	
				16,330		0.6	2.79	
				12,660	1,670	0.5	2.74	
71-2(39)	2	100.0	100.0	15,530		7.4	2.67	6.20
71-7(28)	1	100.0	95.0	10,280		0.9	2.84	5.72
71-8(76)	7	98.9	96.1	8,320		0.6	2.84	
				13,250	2,710	1.9	2.84	
71-15(36)	2	99.5	96.0	8,130		1.5	2.84	
71-17(69)	10	99.0	92.8	10,160		2.7	2.72	
				17,890		1.2	2.83	
				2,800		2.0	2.81	
71-19(70)	10	98.7	92.6	13,620	2,200	0.9	2.86	
				14,360	1,790	1.8	2.77	
71-20(49)	5	99.0	92.4	16,020	1,670	1.3	2.82	
71-21(51)	10	98.4	89.8	10,090		1.2	2.85	
				11,730	2,000	1.0	2.85	
71-22(71)	6	98.8	95.2	12,030		6.7	2.72	
71-29(73)	2	99.5	93.0	14,180	1,600	1.1	2.83	
71-31(61)	2	98.5	94.0	16,940		1.2	2.88	
71-32(79)	9	99.2	86.1	9,470	1,850	0.8	2.82	
71-35(60)	10	99.2	93.5	5,520		2.3	2.84	10.81
71-38(78)	10	99.6	86.2	12,330		1.2	2.76	3.00
71-46(48)	7	99.1	96.1	13,260	1,980	2.5	2.70	5.98
71-48(50)	10	99.4	94.6	17,670		0.7	2.79	
71-51(25)	2	98.5	87.0	17,860	1,900	2.4	2.78	8.15
71-52(46)	6	99.8	95.0 .	10,860				7.29
71-53(58)	10	98.9	92.9	4,600	1,730	1.7	2.81	8.33
71-56(Q-1)	10	99.0	87.2	8,650		2.2	2.81	
71-57(54)	10	99.2	94.7	14,300				
				13,970		0.7	2.79	
				8,220		1.0	2.82	
71-58(19)	2	99.0	86.0	18,590	2,080	0.8	2.78	
71-59(57)	10	98.9	84.9	25,880				
				11,050		2.5	2.76	3.34
71-61(20)	3	99.7	87.3	8,840				
71-62(59)	10	99.3	89.7	8,650		0.5	2.69	
				11,410		1.3	2.82	
71-64(56)	10	97.8	85.6	10,680	2,450	2.0	2.78	
71-69(5)	2	98.0	90.5	11,960		1.1	2.83	
71-71(2)	2	96.0	77.0	18,690		1.9	2.82	
71-77(F-4)	2	100.0	87.0	16,210		0.8	2.83	
71-83(87)	9	99.2	91.1	9,210	1,440	3.2	2.81	5.95
71-87(F-7)	10	99.2	87.5	7,920		1.3	2.83	4.86

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-88(53B)	10	99.4	91.6	3,680		2.4	2.81	
71-89(55)	10	99.0	91.1	11,420		1.9	2.78	4.28
71-90(53A)	10	99.6	86.1	10,680	2,270	1.1	2.77	
71-91(67)	10	98.5	87.3	14,570	2,300	1.3	2.73	
71-93(F-12)	10	97.8	80.4	13,290	1,650	1.5	2.78	
71-95(88)	9	99.5	77.4	13,430	2,540	0.9	2.83	
71-96(88)	7	98.0	85.4	10,870		1.6	2.84	
71-97(Q-3)	10	98.9	83.9	15,270	1,840	1.4	2.84	
				7,650	2,320	2.2	2.81	
Average		99.0	91.1	11,158	1,955	1.7	2.80	7.89
Maximum				25,880	2,710	7.4	2.88	14.88
Minimum				2,490	1,070	0.5	2.67	3.00

TABLE A-5   Strength properties of the Kankakee Formation (Silurian System, Alexandrian Series) in northeastern Illinois (TARP data from Harza Engineering 1975b).

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
74-4	4	96.0	84.5	10,200				8.87
74-5	10	99.6	97.0	6,150				
				10,200				
74-7	7	99.0	95.7	6,690				8.10
				10,220				
				3,570				
74-9	5	96.8	88.8	5,940				
74-16	4	100.0	90.0	5,580				
74-17	6	99.8	96.8	9,700				12.58
74-18	3	100.0	78.7	3,720				
74-24	4	100.0	91.0	7,810				
74-26	4	100.0	99.0	8,360				
74-27	4	100.0	95.0	7,620				
74-28	4	99.8	93.5	8,550				5.20
74-29	3	100.0	96.0	9,850				8.50
74-30	3	100.0	99.0	19,740				15.20
74-31	3	100.0	96.7	7,660				8.03
74-34	3	100.0	72.3	8,990				
				8,220				
				16,540				15.35
74-36	3	100.0	94.0	9,520				11.51
				4,720				
74-38	4	98.0	94.8	8,480				9.44
74-39	4	96.3	90.0	12,270				
74-44	3	100.0	95.7	6,020				5.24
74-45	4	100.0	97.3	8,770				
71-1(52)	5	96.4	92.8	14,250		0.7	2.79	
71-2(39)	7	98.9	95.1	17,190	1,990	0.7	2.80	
71-3(35)	5	99.8	92.2	8,740	2,110	0.9	2.85	8.05
71-6(41)	5	99.2	96.2	9,940	1,780	0.8	2.86	8.58
71-7(28)	5	98.0	89.1	5,580	1,130	1.9	2.82	
71-8(76)	5	99.6	97.4	16,200		1.1	2.81	7.96
				12,780		0.8	2.86	
71-9(31)	5	98.4	94.6	17,360	1,660	1.7	2.81	6.14
71-11(38)	4	97.0	81.0	8,100		0.6	2.86	6.38
71-12(42)	5	97.8	93.6	11,970	1,670	1.0	2.86	
71-13(72)	3	98.3	96.0	12,150	1,560	0.6	2.83	
71-16(43)	5	98.8	96.4	11,050		1.3	2.81	
71-19(70)	4	99.3	92.8	18,225		2.3	2.60	2.85
71-20(49)	7	99.0	77.1	16,940	2,240	1.6	2.84	8.16
				20,410		0.8	2.88	
				10,950	1,180	0.8	2.82	
71-21(51)	4	98.8	89.5	20,770	2,200	1.2	2.81	8.26
71-22(71)	4	98.3	90.8		2,400	1.0	2.83	
71-23(6)	5	98.4	74.6	23,560	1,750	0.9	2.79	
71-24(47)	8	98.3	90.5	15,690		1.6	2.84	
				12,810	2,330	0.5	2.82	
71-25(62)	6	99.0	89.5	10,460		1.1	2.84	
71-29(73)	3	98.7	78.7	12,130		0.6	2.81	
71-31(61)	6	99.2	95.5	21,060		1.4	2.87	
				7,920	2,060	1.5	2.88	
71-32(79)	5	96.6	86.6	15,080	1,690	1.3	2.78	
71-33(30)	4	98.8	85.8	10,680	1,980	0.7	2.81	
71-34(81)	5	96.4	85.4	18,590		0.4	2.82	
71-37(32)	4	98.8	91.3	15,830		0.2	2.80	
71-41(74)	4	98.8	92.5	6,440		0.8	2.80	
71-42(27)	6	99.0	85.3	16,020	1,550	1.2	2.77	
				6,630		0.7	2.80	7.49
71-43(77)	4	99.8	87.8	12,340		0.6	2.80	
71-44(29)	6	99.3	89.3	18,410	1,850	1.5	2.82	6.73
71-46(48)	6	98.5	79.8	16,200	1,370	1.2	2.80	
71-47(23)	4	99.0	83.8	21,720		0.9	2.81	
71-48(50)	4	98.5	92.0	16,940				
				12,400				
71-50(12)	2	98.5	81.5	9,940		1.7	2.76	
71-52(46)	5	99.2	85.0	27,970		1.2	2.78	
71-53(58)	4	99.3	84.0	11,660		0.5	2.82	

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-55(F-10)	6	99.3	77.7	14,940	1,440	1.1	2.79	5.58
71-56(Q-1)	4	100.0	73.5	7,730		2.5	2.79	
71-57(54)	4	99.5	86.5	9,860		1.8	2.83	
71-58(19)	3	99.7	74.3	21,540		1.2	2.79	9.06
71-59(57)	4	99.0	89.3	8,100	1,980	1.0	2.78	
71-60(Q-2)	2	99.5	83.0	9,840		1.5	2.82	6.86
71-64(56)	3	98.7	73.7	7,810	1,810	1.7	2.80	9.13
71-66(1)	4	99.8	83.3	17,150		0.8	2.83	
71-68(9)	4	99.8	84.8	7,220		1.1	2.78	7.60
71-70(14)	4	99.8	88.3	11,290		0.5	2.82	
71-72(18)	4	99.8	68.0	7,730		1.9	2.83	
71-73(15)	4	96.5	83.5	18,390		2.3	2.89	
71-75(17)	4	99.3	66.5	12,890		0.9	2.83	
71-76(8)	4	98.3	79.8	12,890				11.36
71-78(F-8)	4	99.3	83.3	14,570		0.8	2.81	
71-81(F-2)	3	100.0	64.7	9,830		1.5	2.83	
71-82(96)	5	94.4	75.8	9,470	2,940	1.6	2.81	
71-85(95)	4	99.8	69.5	6,920		5.5	2.82	
71-88(53B)	5	99.2	76.6	7,180		0.8	2.84	
71-89(53)	3	99.3	84.0	8,280	2,140	0.9	2.81	
71-90(53A)	4	98.8	70.8	10,680	2,270	1.1	2.87	
71-91(67)	5	98.4	72.8	9,390		0.5	2.81	
71-94(F-11)	4	98.8	64.5	16,380	2,600	1.1	2.84	
71-95(88)	5	99.6	77.0	14,210		1.7	2.82	
71-96(88)	4	100.0	88.3	13,470		0.5	2.84	
71-97(Q-3)	4	98.3	82.3	12,930	2,460	2.3	2.86	
Average		98.8	86.5	11,944	1,931	1.2	2.82	8.45
Maximum				27,970	2,940	5.5	2.89	15.35
Minimum				3,570	1,130	0.2	2.60	2.85

TABLE A-6 Strength properties of the Wise Lake and Dunleith Formations (Ordovician System, Galena Group) in northeastern Illinois (TARP data from Harza Engineering Company 1975b).

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-1(52)	8	98.8	93.9	7,300	1,640	0.4	2.77	
				6,920		1.0	2.81	
				7,830	1,960	1.1	2.78	
				6,040		1.3	2.78	7.35
				8,560	2,270	2.2	2.81	
				4,420		1.6	2.78	
				6,440	1,670	2.9	2.78	
71-2(39)	21	97.6	87.5	18,760	1,830	0.6	2.82	
				8,200		1.8	2.83	
				5,100	1,160	0.6	2.80	8.50
				14,940		0.5	2.79	
				7,650	1,460	0.4	2.79	
				13,840		0.4	2.71	
71-7(28)	10	96.3	82.9	11,100	1,810	0.3	2.81	
				8,990		0.3	2.81	
				6,260	1,040	0.4	2.80	5.07
				7,810		2.2	2.77	
				9,790	680	0.3	2.74	
71-8(76)	19	99.1	91.2	9,390	2,020	1.0	2.89	
				3,130	1,110	2.6	2.84	8.65
				16,090		2.3	2.86	
				4,970	1,450	3.1	2.85	
				10,120		1.6	2.87	
71-9(31)	19	98.6	90.2	15,540	2,350	0.5	2.79	
				14,210		1.3	2.82	
				5,150	1,710			6.63
71-10(45)	11	98.2	93.0	15,280	1,730	0.3	2.74	
						1.0	2.78	
				8,760	1,420	0.8	2.81	
				6,440		1.8	2.74	6.18
				7,140		1.9	2.77	
				9,720	2,130	1.7	2.77	
71-11(38)	12	85.8	65.3	6,810	900	1.2	2.87	
				5,155		0.3	2.85	9.11
				7,360	2,270	0.1	2.84	
				4,970		0.2	2.76	
71-13(72)	19	99.1	81.9	13,440	1,560	0.9	2.82	
				16,020		9.7	2.76	
				10,680	1,060	1.7	2.83	
				12,890		3.0	2.84	
				8,300	1,330	3.3	2.82	
71-17(69)	19	98.4	87.1	14,510	1,480	1.1	2.82	
				13,110		0.5	2.81	
				11,050	2,100	0.4	2.85	
				8,280			2.77	12.38
				12,890	2,020	0.1	2.77	
				12,670		0.4	2.80	
71-19(70)	19	98.5	88.3	6,810		1.4	2.83	
				10,310	1,870	0.6	2.88	
				11,230		2.6	2.83	7.00
				4,420	1,400	5.0	2.81	
				6,075		4.6	2.85	
				14,250	1,030	0.1	2.72	
				9,920		0.8	2.81	
71-20(49)	19	98.8	82.9	17,670	1,370	0.4	2.84	
				11,860		0.2	2.78	
				8,840	2,050	0.3	2.81	9.60
				9,430	.	1.3	2.77	
				5,410	1,450	0.8	2.74	
71-21(51)	20	99.2	89.6	15,460	1,710	0.7	2.86	
				7,550		0.9	2.80	
				9,940		2.3	2.75	6.48
71-22(71)	19	99.4	80.8	13,670	1,790	0.9	2.84	
				7,730		0.7	2.83	
				5,520	1,290	2.6	2.83	
				6,260		1.8	2.84	
				5,710	2,170	1.3	2.82	
71-23(6)	19	98.5	72.0	11,050		0.9	2.81	10.85

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
				9,210		0.9	2.82	
				13,000	1,960	0.9	2.81	
				8,730	1,260	0.3	2.86	11.58
71-26(7)	20	99.0	84.9	10,310	2,070	1.9	2.83	
				7,180		2.1	2.83	
71-27(33)	20	99.5	87.8	13,260	1,890	0.3	2.85	
				6,330		0.2	2.75	
71-28(10)	19	95.6	72.9	10,010	2,680	0.5	2.80	
				7,360		0.4	2.84	
				6,700	970	0.8	2.81	
				14,180	1,830	0.8	2.88	
71-29(73)	20	99.2	89.0	13,440	1,610	0.3	2.82	
				7,920			2.81	
				15,460	1,170	2.2	2.77	7.94
				4,400		2.4	2.69	
				8,100	1,190	4.0	2.76	
				8,820		0.5	2.79	
71-30(75)	20	99.4	89.3	5,460	1,090	0.6	2.78	9.63
				6,130		1.2	2.83	
				10,560		0.2	2.73	
71-32(79)	18	99.2	88.6	14,100	870	2.0	2.83	
				12,020		1.2	2.84	
				4,790		1.9	2.84	10.11
				6,740		2.8	2.82	
				19,130		0.7	2.81	11.40
71-33(30)	20	99.6	79.5	7,000	1,390	1.6	2.82	8.92
				7,360		1.1	2.79	
71-34(81)	19	98.8	83.6	9,880		0.3	2.83	
				16,380		0.7	2.83	11.50
				13,930	1,800	1.2	2.83	
				6,190		0.9	2.82	
				14,750	1,100	4.6	2.83	
71-36(80)	19	99.8	79.7	18,590		1.1	2.83	
				14,800	1,620	0.7	2.83	
				6,650		1.3	2.83	
71-37(32)	19	99.1	85.8	11,230	1,590			
				7,000				
				11,780	1,370	2.4	2.70	11.91
71-38(78)	19	99.8	84.0	7,550	1,670		2.81	9.75
				12,890	1,350		2.78	
				4,690	1,290			
71-39(82)	19	99.5	87.2	13,440	1,520	0.8	2.77	8.70
				14,040		0.2	2.81	
				11,410	860	1.4	2.75	
				14,530				
71-41(74)	18	99.2	93.6	8,840	1,970	1.2	2.79	
				7,000		3.8	2.83	
				5,520		4.3	2.83	
				8,650		4.8	2.78	8.11
71-42(27)	16	99.5	83.3	8,470		0.7	2.79	
				7,000		2.9	2.80	
				6,630		0.4	2.80	8.20
				8,290				
				3,830	2,435	0.2	2.83	
71-43(77)	18	99.0	95.1	13,150				
				10,280	1,340	0.6	2.82	6.84
71-44(29)	19	98.9	81.7	7,810	730	2.6	2.81	
				6,440		5.3	2.82	
				17,400		0.6	2.81	
				10,310		1.2	2.81	5.09
				8,560		1.4	2.82	
71-46(48)	20	99.3	92.8	12,520		0.3	2.82	
				18,410	1,630	0.4	2.78	10.87
				5,710				
				14,730	1,330	6.7	2.79	
				14,730		3.2	2.78	
				10,360	1,620	0.4	2.72	
				21,540		0.1	2.72	10.35

TABLE A-6   (continued)

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-48(50)	20	97.9	85.8	14,910	1,810	1.0	2.88	
				14,180		0.3	2.79	9.70
				18,410				
				10,570		1.1	2.79	
				9,210		1.8	2.78	
71-49(53)	20	93.5	60.5	8,840		0.7	2.79	
				8,100	900	1.7	2.79	6.14
71-56(Q-1)	18	99.0	88.6	5,150		4.5	2.80	
71-57(54)	22	98.4	72.0	12,950		0.6	2.80	
				22,420				
				11,920		2.0	2.81	9.09
71-60(Q-2)	19	99.6	81.0	10,860		1.2	2.82	
71-63(89)	20	99.4	79.6	8,740		1.5	2.83	
71-65(F-9)	19	98.9	91.6	11,200	1,400	0.2	2.80	
71-67(66)	19	99.4	82.6	10,020		1.4	2.78	
71-76(8)	4	100.0	64.8	10,720		2.1	2.84	
71-79(F-3)	20	97.4	72.4	6,260	2,790	2.3	2.82	
71-81(F-2)	18	99.1	82.8	8,840		0.2	2.78	
71-84(F-5)	20	99.5	79.4	9,650	2,250	1.8	2.83	
71-86(F-6)	19	98.7	87.9	10,680	1,890	0.7	2.81	
71-88(53B)	21	93.2	65.2	7,000	1,750	2.2	2.83	
71-90(53A)	19	98.3	69.3	9,020	1,910	0.9	2.83	
71-95(83)	19	99.2	80.6	6,810		3.3	2.83	
				8,660	1,140	2.3	2.85	
				11,590		0.9	2.78	
71-96(88)	19	98.8	75.7	9,470		1.2	2.84	
				9,100	1,640	1.5	2.84	
71-97(Q-3)	18	99.1	72.2	9,720	1,510	1.3	2.85	
				6,400	1,710	3.4	2.84	
				6,550		5.5	2.79	
				6,550	2,070			
Average		98.4	82.5	10,008	1,598	1.5	2.81	8.83
Maximum				22,420	2,790	9.7	2.89	12.38
Minimum				3,130	680	0.1	2.69	5.07

TABLE A-7 Strength properties of the Platteville Group (Ordovician System) in northeastern Illinois (TARP data from Harza Engineering Company 1975b).

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
71-1(52)	7	97.1	89.7	24,670		1.1	2.82	8.80
					2,510	0.3	2.81	
				13,480		0.1	2.78	
				18,660	950	1.2	2.81	
71-2(39	12	99.7	97.4	26,050	1,870	0.2	2.76	9.45
				29,330		0.2	2.74	
				32,060	2,310	0.3	2.71	
				22,950		0.8	2.82	
				21,310		0.9	2.78	9.30
71-7(28)	6	97.5	82.7	12,700	2,510	1.8	2.72	9.90
				16,940		0.2	2.76	
				17,450		0.3	2.75	
				8,820	1,590	0.2	2.80	
71-8(76)	14	99.4	91.6	10,120		2.0	2.84	
				18,040	2,510	0.6	2.80	
71-9(31)	12	98.8	90.5	8,030		0.3	2.79	
				10,310	990	1.4	2.77	6.09
71-10(45)	6	99.5	95.7	25,550		2.3	2.77	
				18,040		0.7	2.73	9.65
				20,400	2,280	0.5	2.74	
71-11(38)	7	92.6	62.9	16,570	2,160	0.5	2.78	
				6,630		1.2	2.76	5.28
				11,970	2,230	0.6	2.82	
71-13(72)	12	99.0	57.3	34,240		1.9	2.84	
					2,200	1.6	2.81	
				19,880		0.7	2.86	12.20
71-17(69)	10	94.8	77.8	13,070	1,370	1.6	2.78	11.61
				11,230		0.2	2.83	
				8,650	1,380	3.9	2.82	7.22
				11,450		4.3	2.71	
71-19(70)	12	98.8	85.0	5,340	870	0.6	2.73	
				14,840		1.6	2.84	
				5,150		1.2	2.82	7.47
				15,280		0.7	2.82	9.90
71-20(49)	13	98.6	83.1	11,640		0.1	2.73	
				19,880	1,540	0.2	2.79	
				6,990	2,310	0.3	2.72	
71-21(51)	11	99.6	83.5	13,260		0.1	2.73	
				12,890	2,240	0.1	2.77	9.13
71-22(71)	12	98.6	83.7	10,490		1.1	2.82	
71-23(6)	12	95.4	74.3	21,650		0.3	2.75	
				4,930		0.3	2.81	
				12,700		1.9	2.79	10.60
71-26(7)	11	99.5	84.3	11,230		0.4	2.74	
				12,520	2,500	0.4	2.73	
71-28(10)	12	98.4	87.3	13,070		1.3	2.80	
				28,350	2,100	1.4	2.80	
				17,890		1.1	2.81	9.96
71-29(73)	13	98.2	84.8	10,430	1,450	0.3	2.80	
				14,950		0.1	2.79	10.20
				43,930	1,930	0.4	2.82	
				22,090		0.5	2.80	
71-30(75)	13	98.9	93.3	21,870	1,520	0.7	2.81	
				9,790	1,740	0.5	2.79	
				16,270		0.4	2.57	
71-32(79)	13	99.6	85.5	8,380	3,780	0.3	2.83	
				8,560		2.7	2.83	9.12
				15,850		0.7	2.81	8.69
71-33(30)	12	99.3	92.8	13,260	2,190	0.4	2.85	8.96
				19,700		0.7	2.74	11.68
				8,100	2,080	0.3	2.79	
71-34(81)	13	99.2	82.0	11,110	1,480	1.6	2.83	9.96
				28,800		3.5	2.75	
71-36(80)	13	99.4	81.8	19,880		1.4	2.82	11.82
				7,860	1,850	0.2	2.83	
				16,380		1.8	2.81	9.43
71-37(32)	12	100.0	83.5	9,570	1,750	0.4	2.79	7.53
71-38(78)	13	99.3	86.3	20,620		0.1	2.84	9.08

Borehole	Core Runs	Average Core Recovery (%)	Average RQD (%)	Unconfined Compressive Strength (PSI)	Tensile Strength (PSI)	Moisture Content (%)	Specific Gravity	Static Modulus (PSIx10E6)
				12,750				
				11,050				
71-39(82)	13	99.5	91.8	5,150	1,340			
				7,180	1,450	2.0	2.83	
71-41(74)	13	99.7	85.2	7,730	2,130	1.0	2.77	9.52
				20,740		1.5	2.82	
				5,470	760	1.1	2.79	
				3,320		4.5	2.82	10.39
71-42(27)	13	99.5	66.5	13,230		0.6	2.81	
				10,310				8.03
71-43(77)	13	98.9	92.6	14,180				
				9,360				
				8,630		0.8	2.77	
				11,920	1,440	0.5	2.80	8.12
71-44(29)	12	98.8	88.7	9,570	1,320	2.7	2.80	4.76
				15,460		0.2	2.72	
				22,460		0.7	2.79	8.10
71-46(48)	13	98.1	96.3	24,300	2,020	0.3	2.73	
				15,830		0.5	2.73	
				11,970	2,140	0.2	2.69	10.76
				5,350		1.2	2.81	
71-48(50)	14	97.9	89.4	14,360		0.5	2.75	5.52
				25,040		0.3	2.76	
				24,300		0.2	2.70	
				13,260		0.9	2.80	9.54
71-49(53)	13	99.4	68.1	8,840	1,460	0.7	2.82	15.93
				24,300		2.0	2.79	
				25,720				
71-63(89)	12	99.3	92.3	7,280	2,380	10.5	2.81	
71-65(F-9)	13	99.2	94.2	12,540		0.4	2.69	7.48
71-67(66)	12	99.7	74.6	4,790		7.3	2.89	
				9,210	2,090	0.8	2.74	8.26
71-79(F-3)	12	99.7	67.0	6,540	1,600	0.9	2.82	
71-81(F-2)	13	99.2	88.2	11,410		0.1	2.72	
				11,780	2,520	0.2	2.71	
				8,470		3.0	2.82	
71-84(F-5)	13	98.6	82.1	23,310		1.4	2.78	
				9,650	2,320	1.5	2.77	
				8,650		1.0	2.84	
71-86(F-6)	12	97.3	70.3	2,950		2.3	2.82	
				26,880	1,590	1.1	2.82	
71-88(53B)	13	99.5	76.0	15,280	2,830	1.0	2.84	
				13,260		0.6	2.81	
71-90(53A)	13	99.0	48.0	12,600		0.6	2.81	
71-95(83)	13	96.8	66.6	8,920	1,970	2.5	2.74	
				14,020	1,630	0.5	2.76	
71-96(88)	13	98.8	68.7	4,010		0.7	2.83	
				31,490	2,320	0.8	2.83	
				15,890		0.8	2.84	
71-97(Q-3)	13	99.1	89.5	19,480	2,770	0.5	2.78	
				15,730	2,720	0.3	2.73	
				17,400	2,380	0.3	2.74	
				17,110	2,940	0.6	2.74	
Average		98.7	82.1	14,828	1,968	1.1	2.78	9.17
Maximum				43,930	3,780	10.5	2.89	15.93
Minimum				2,950	760	0.1	2.57	4.76

TABLE B-1 ISGS geotechnical data for Silurian bedrock samples from SSC study area.

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso-tropy
F-1-77.6	Dolomite	12,686	2.63	758	2,208	3.69	2.64	40	690	3.2
F-1-77.9	Dolomite	17,592	3.32	979	2,138	1.66	2.65	65	979	2.2
F-1-84.4	Dolomite	15,555		987	1,928	2.60	2.59	44	529	3.6
F-1-109.8	Dolomite	16,594	9.41	1,269	2,591	0.54	2.67	60	485	5.3
F-1-140.85	Dolomite	13,182		1,166	1,907	0.46	2.80	62	512	3.7
F-1-197.1	Dolomite	9,942	2.84	1,138	1,815	2.01	2.66	54	390	4.7
F-2-118.4	Dolomite	20,187	10.29	1,314	2,306	0.50	2.71	67	765	3.0
F-2-128.05	Dolomite	10,015	12.55	1,388	2,716	0.10	2.74	67	893	3.0
F-2-139.7	Dolomite	16,905	10.95	973	2,444	0.20	2.71	54	621	3.9
F-2-156.9	Dolomite	15,007	3.39	1,315	2,932	0.20	2.79	70	707	4.1
F-4-126.2	Dolomite	14,891	9.73	1,435	1,894	1.34	2.50	59	584	3.2
F-4-128	Dolomite	21,496	4.09	1,720	3,330	0.50	2.72	66	927	3.6
F-6-99.7	Dolomite	17,887	10.94	1,074	2,551	1.40	2.67	52	816	3.1
F-6-125	Dolomite	23,458	5.77	1,213	2,098	0.99	2.74	67	473	4.4
F-6-151.9	Dolomite	15,130	3.34	1,104	1,906	1.80	2.68	44	549	3.5
F-7-85.5	Dolomite	20,918	11.56	1,016	2,023	1.41	2.68	52	569	3.6
F-10-91.5	Limestone	11,945	9.37	914	1,488	2.13	2.71	54	530	2.8
F-10-102.7	Limestone	15,772	3.84	1,089		1.99	2.64	45		
	Average	16,065	7.13	1,158	2,251	1.31	2.68	57	648	3.6
	Maximum	23,458	12.55	1,720	3,330	3.69	2.80	70	979	5.3
	Minimum	9,942	2.63	758	1,488	0.10	2.50	40	390	2.2

TABLE B-2 ISGS geotechnical data for Maquoketa Group (Ordovician) dolomitic shale and shale samples from the SSC study area.

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso-tropy
F-1-249.5	Dolo-Shale	6,307	1.43	623	851	3.12	2.64	40	357	2.4
F-1-261.7	Dolo-Shale	6,664	1.02	589	1,095	3.47	2.58	30	245	4.5
F-1-271.2	Dolo-Shale	6,541	3.32	513	395	3.32	2.57	40	205	1.9
F-1-288.5	Dolo-Shale	5,933	0.90	811	905	3.31	2.50	36	200	4.5
F-1-297.9	Dolo-Shale	4,150	0.65	674	1,279	3.16	2.50	34	335	3.8
F-1-299.1	Dolo-Shale	5,859	1.13	528	1,147	3.27	2.56	32	432	2.7
F-1-301.7	Dolo-Shale	4,377	0.68	475	731	3.88	2.51	20	122	6.0
F-1-306.6	Dolo-Shale	549	0.48	497	242	4.96	2.51	14	96	2.5
F-1-308.1	Dolo-Shale	3,727	0.44	347	614	4.35	2.57	14	119	5.2
F-1-318.8	Dolo-Shale	3,117	0.37	538	356	4.76	2.45	11	224	1.6
F-1-345	Shale	1,802	0.36	308	349	4.22	2.48	17	67	5.2
F-2-168.2	Shale	5,707	0.93	420	830	3.80	2.46	34	186	4.5
F-2-181.8	Shale	4,253	0.84	349	538	5.00	2.61	20	104	5.2
F-2-189.4	Shale	3,678	0.66	349	570	4.60	2.52	23	157	3.6
F-2-200.3	Shale	3,358	0.44	465	440	5.40	2.41	20	126	3.5
F-2-208.2	Shale	3,601	0.38	364	404	6.00	2.42	20	112	3.6
F-2-219.95	Shale	3,039	0.47	377	497	5.40	2.43	32	162	3.1
F-2-267.85	Dolo-Shale	4,318	0.94	470	454	3.70	2.49	45	135	3.4
F-2-275.65	Dolo-Shale	4,148	0.66	515	543	4.00	2.46	42	245	2.2
F-2-318.4	Dolo-Shale	3,534	0.35	395	359	6.10	2.37	26	64	5.6
F-2-334.8	Shale	3,488	0.18	478	447	4.30	2.33	33		
F-2-347.4	Shale	3,012	0.33	408	374	5.60	2.33	30	50	7.5
F-2-359.15	Shale	2,823	0.44	256	432	3.70	2.40	26	106	4.1
F-2-362	Shale	3,235	0.59	416	401	4.39	2.39	24	354	1.1
F-2-364.65	Shale	3,069	1.11	347	419	6.12	2.40	20	86	4.9
F-3-119.75	Dolo-Shale	4,090	0.51	739	1,369	4.30	2.48	24	319	4.3
F-3-150.4	Dolo-Shale	3,629	0.45	477	2,199	4.00	2.40	27	829	2.7
F-3-160	Dolo-Shale	3,723	0.46	493	776	5.10	2.42	23	275	2.8
F-3-166.2	Dolo-Shale	4,064	0.52	526	521	4.70	2.52	21	99	5.3
F-3-189.9	Shale	2,353	0.43	488	317	6.00	2.42	25	488	0.6
F-3-197.9	Shale	4,726	0.55	522	425	5.30	2.38	21	112	3.8
F-3-206.4	Shale	4,270	0.61	477	535	4.90	2.41	21	114	4.7
F-3-216.3	Shale	5,111	0.95	431	471	2.60	2.42	26	124	3.8
F-4-158.5	Dolo-Shale	2,177	0.22	273	750	6.00	2.40	17	125	6.0
F-4-162.5	Dolo-Shale	2,107	0.22	175	361	5.60	2.47	17	63	5.7
F-4-171.45	Dolo-Shale	2,538	0.36	332	335	6.50	2.51	23	79	4.2
F-4-183.5	Dolo-Shale	4,633	0.91	401	541	3.40	2.47	26	152	3.6
F-4-196.2	Dolo-Shale	4,114	1.21	613	1,110	3.70	2.57	32	339	3.3
F-4-208.3	Dolo-Shale	3,122	1.94	654	877	2.70	2.67	47	254	3.5
F-4-215.75	Dolo-Shale	5,192	1.50	657	1,005	1.90	2.79	27	216	4.7
F-4-321.4	Shale	4,455	0.49	456	363	5.30	2.40	27	90	4.0
F-4-327.05	Shale	4,137	0.52	559	635	5.40	2.56	20	163	3.9
F-5-205.2	Dolo-Shale	4,500	0.43	872	1,358	4.40	2.38	22	95	14.3
F-5-210.9	Dolo-Shale	4,136	0.52	742	455	4.90	2.40	29	125	3.6
F-5-224.3	Dolo-Shale	4,195	0.61	393	492	5.60	2.37	25	61	8.1
F-6-198.4	Dolo-Shale	4,830	0.68	763	1,307	3.70	2.63	27	271	4.8
F-6-249.6	Dolo-Shale	4,829	1.28	631	902	2.40	2.45	30	200	4.5
F-6-267.4	Dolo-Shale	7,713	2.31	534	482	2.00	2.42	29	141	3.4
F-6-279	Shale	5,821	0.97	492	472	2.50	2.42	24	114	4.1
F-6-297.4	Shale	2,473	0.26	348	233	4.00	2.46	16	22	10.6
F-7-139.1	Shale	5,997	0.80	659	973	1.60	2.66	42	273	3.6
F-7-185.5	Dolo-Shale	4,601	0.50	615	1,542	4.60	2.52	21	854	1.8
F-9-197.6	Dolo-Shale	7,227	1.37	661	1,086	0.74	2.62	52	458	2.4
F-9-226.2	Dolo-Shale	3,377	0.35	798	1,040	5.22	2.66	28	417	2.5
F-9-236.8	Dolo-Shale	9,358	1.63	594	569	1.77	2.57	42	156	3.6
F-10-232.2	Shale	3,166	0.44	397	408	7.18	2.36	13	61	6.7
F-10-239.9	Shale	3,447	0.47	480	441	6.84	2.34	20	80	5.5
F-10-251.2	Shale	3,827	0.55	437	402	5.17	2.37	11	118	3.4
F-15-233.2	Shale	6,980	0.70	775	910	1.05	2.52	32	195	4.7
F-15-269.7	Dolo-Shale	10,866	2.46	908	1,216	0.77	2.59	39	436	2.8
F-15-306.7	Dolo-Shale	5,455	0.63	650	560	4.70	2.41	30	90	6.2
F-15-317.8	Dolo-Shale	5,130	0.62	660	450	4.77	2.43	28	60	7.5
F-15-329.85	Dolo-Shale	5,254	0.71	640	500	4.82	2.39	30	70	7.1
F-16-149.2	Lim-Shale	4,409	0.66	630	1,080	3.26	2.58	33	410	2.6
F-16-178.2	Lim-Shale	3,988	0.47	540	450	4.94	2.43	22	80	5.6
	Average	4,405	0.77	523	686	4.22	2.48	27	202	4.3
	Maximum	10,866	3.32	908	2,199	7.18	2.79	52	854	14.3
	Minimum	549	0.18	175	233	0.74	2.33	11	22	0.0

TABLE B-3 ISGS geotechnical data for Maquoketa Group (Ordovician) dolomite samples from the SSC study area.

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso- tropy
F-1-296.4	Dolomite			738	1,189	2.96	2.56	41	560	2.1
F-1-305	Dolomite	8,183		770	1,113	2.70	2.57	31	264	4.2
F-1-311.8	Dolomite	10,490		1,314	1,506	0.82	2.81	53	622	2.4
F-1-313.2	Dolomite	11,400	3.34	989	2,394	0.47	2.81	63	649	3.7
F-2-238.3	Dolomite	7,677	5.69	579	2,591	2.70	2.48	43	611	4.2
F-2-297.25	Dolomite	6,233	0.64			1.60	2.87	51		
F-4-223.4	Dolomite	6,205	2.84	847	1,197	1.80	2.37	58	316	3.8
F-4-236.55	Dolomite	9,465	3.66	715	893	2.10	2.46	54	294	3.0
F-4-277.8	Dolomite	15,226	4.20	783	1,609	0.50	2.14	68	374	4.3
F-4-284.3	Dolomite	7,815	1.49	1,177	1,660	2.60	2.53	54	915	1.8
F-4-304.55	Dolomite	5,063	1.40	780	1,778	2.60	2.75	44	485	3.7
F-6-178.3	Dolomite	12,143	9.06	790	1,689	0.82	2.67	61	362	4.7
F-6-183.6	Dolomite	7,037	1.54	877	1,455	1.70	2.66	54	397	3.7
F-6-222.5	Dolomite	6,786	1.98	672	643	1.20	2.53	75	246	2.6
F-7-107.3	Dolomite	7,317	0.98	869	1,013	0.63	2.69	38	303	3.3
F-7-151.6	Dolomite	14,833	5.99	684	543	1.20	2.63	64	130	4.2
F-7-212.6	Dolomite	8,100	0.98	717	886	1.04	2.50	32	163	5.4
	Average	8,998	3.13	831	1,385	1.61	2.59	52	418	3.4
	Maximum	15,226	9.06	1,314	2,591	2.96	2.87	75	915	5.4
	Minimum	5,063	0.64	579	543	0.47	2.14	31	130	0.0

TABLE B-4 ISGS geotechnical data for Maquoketa Group (Ordovician) limestone samples from the SSC study area.

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso- tropy
F-12-142.4	Limestone	20,074	3.90	1,343	1,743	0.13	2.76	60	1,227	1.4
F-12-229.5	Limestone	22,422	6.24	1,303	2,067	1.06	2.75	64	655	3.2
F-12-257.1	Limestone	20,687	2.76	1,090	1,749	0.81	2.66	76	786	2.2
F-15-204	Limestone	19,417	3.94	1,518	1,322	0.11	2.71	56	648	2.0
F-16-76.5	Limestone	10,976	1.42	1,055	1,726	0.38	2.64	47	345	5.0
F-16-100.9	Limestone	10,828	1.75	820	1,230	2.54	2.61	37	430	2.9
F-16-114.05	Limestone	6,228	0.99	520	920	3.77	2.51	31	230	4.0
	Average	15,805	3.00	1,093	876	2.53	2.32	35	274	3.6
	Maximum	22,422	6.24	1,518	2,067	3.77	2.76	76	1,227	5.0
	Minimum	6,228	0.99	520	920	0.11	2.51	31	230	1.4

TABLE B-5 ISGS geotechnical data for samples from the Wise Lake Formation (Ordovician, Galena Group) in the SSC study area.

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso-tropy
F-1-349.3	Dolomite	10,766	3.34	936	2,365	0.98	2.75	76	776	3.0
F-1-381.2	Dolomite	6,889	4.39	640		0.41	2.66	58	340	
F-1-395.6	Dolomite	9,130	4.05	895	1,347	0.17	2.65	57	861	1.6
F-1-430.4	Dolomite	10,461	3.96	1,069		0.17	2.75	64	770	
F-1-502.2	Dolomite	6,235	9.38	491		1.46	2.60	66	372	
F-2-369.13	Dolomite	14,594	8.85	845	1,092	0.32	2.78	75	1,010	1.1
F-2-369.6	Dolomite	17,437	5.36	1,432	1,925	0.26	2.74	81	471	4.1
F-2-374.45	Dolomite	14,916	12.86	1,240	2,202	0.69	2.69	66	444	5.0
F-2-380.2	Dolomite	12,909	3.97	1,316	1,332	0.28	2.63	72	396	3.4
F-2-383.5	Dolomite	13,189	12.76	995	1,096	1.07	2.69	68	558	2.0
F-2-389.4	Dolomite			906	1,620		2.72		636	2.5
F-2-396.2	Dolomite	11,092	2.98	746	1,392	1.55	2.72	61	242	5.8
F-2-397.1	Dolomite	11,231	3.19	948	1,153	1.79	2.72	66	665	1.7
F-2-398.4	Dolomite	7,979	8.54	763	800	1.71	2.66	63	342	2.3
F-2-409.2	Dolomite	5,166	1.79	1,194	1,286	2.39	2.69	49	605	2.1
F-2-410.1	Dolomite	13,805	3.32	926	1,820	1.57	2.74	56	588	3.1
F-2-412.3	Dolomite	7,553	2.80	747	1,466	1.70	2.73	61	171	8.6
F-2-415.8	Dolomite	9,097	2.93	638	1,285	2.58	2.53	61	528	2.4
F-2-418.4	Dolomite	8,472	3.16	718	1,453	1.80	2.64	60	693	2.1
F-3-224.35	Dolomite	10,335	9.57	1,209	2,528	0.20	2.67	76	685	3.7
F-3-237.85	Dolomite	8,960	3.29	854	1,885	1.80	2.68	44	407	4.6
F-3-245.8	Dolomite	9,369	3.72	788	1,205	1.20	2.58	63	470	2.6
F-3-274.85	Dolomite	6,153	2.68	534	1,270	2.10	2.59	48	333	3.8
F-3-308.55	Dolomite	12,593	10.71	1,034	2,911	0.10	2.76	69	966	3.0
F-4-336.8	Dolomite	10,354	3.63	979	1,611	1.40	2.72	62	351	4.6
F-4-341.7	Dolomite	10,311	3.20	926	1,344	1.71	2.69	60	613	2.2
F-4-349.2	Dolomite	7,437	9.20	780	1,590	2.50	2.66	56	429	3.7
F-4-359.2	Dolomite	10,051	9.04	758	1,237	2.25	2.60	58	475	2.6
F-5-243.2	Dolomite	6,955	6.87	923	1,341	0.83	2.74	56	383	3.5
F-5-248.9	Dolomite	9,860	3.93	739	1,148	1.60	2.66	45	423	2.7
F-5-258.2	Dolomite	12,438	3.97	1,092	1,429	0.76	2.73	52	412	3.5
F-5-266.7	Dolomite	9,475	3.76	753	1,306	1.50	2.65	48	493	2.6
F-5-335.9	Dolomite	9,320	4.66	506	1,166	1.30	2.62	51	477	2.4
F-5-363.4	Dolomite	6,959	2.20	765		3.28	2.60	53		
F-5-366.6	Dolomite	10,425	4.76	816	1,387	1.40	2.63	49	485	2.9
F-5-367.6	Dolomite	12,597	13.01	810		2.46	2.58	52	720	
F-6-318.8	Dolomite	7,261	9.43	878	1,992	2.10	2.55	57	449	4.4
F-6-331	Dolomite	10,052	3.38	989	1,417	0.76	2.72	53	492	2.9
F-6-336.6	Dolomite	8,211	3.34	1,233	1,710	0.74	2.63	51	845	2.0
F-6-342.7	Dolomite	15,146	2.19	792	1,871	0.64	2.68	72	541	3.5
F-7-229.3	Dolomite	8,816	4.15	802	1,575	1.10	2.75	67	681	2.3
F-7-256	Dolomite	10,282	13.73	712	1,709	1.90	2.78	56	489	3.5
F-7-291.9	Dolomite	7,973	12.12	673	1,297	2.10	2.69	48	481	2.7
F-7-326.1	Dolomite	9,782	4.28	620	1,109	1.93	2.57	60	582	1.9
F-7-356.6	Dolomite	10,216	4.36	579	932	1.40	2.65	62	720	1.3
F-9-260	Dolomite	10,813	3.86	630	929	1.76	2.44	46	421	2.2
F-9-285.8	Dolomite	9,771	3.90	842	1,024	0.87	2.65	59	304	3.4
F-9-325.1	Dolomite	9,508	4.06	567	746	1.79		47	478	1.6
F-9-367.3	Dolomite	15,226	14.05	835	1,234	1.31	2.53	47	437	2.8
F-11-127.6	Dolomite	12,138	9.18	529	1,764	0.84	2.70	63	336	5.3
F-11-154.4	Dolomite	10,167	3.60	929	1,457	2.65	2.67	57	454	3.2
F-11-168.3	Dolomite	6,112	7.80	898	1,578	2.12	2.48	58	548	2.9
F-11-187.15	Dolomite	6,252	3.85	1,059	1,310	2.68	2.60	51	404	3.2
F-11-206.25	Dolomite	2,436	2.16	401	712	3.12	2.61	45	176	4.0
F-11-230.7	Dolomite	3,697	1.79	1,294		2.82	2.63	58		
F-12-267.6	Dolomite	6,029	3.23	937	1,167	1.87	2.65	38	429	2.7
F-12-298.25	Dolomite	6,782	3.53	553	833	3.02	2.56	45	242	3.4
F-12-337	Dolomite	6,940	3.38	402		4.47	2.45	37	.	
F-12-377.15	Dolomite	9,545	4.08	632	782	3.82	2.56	45	557	1.4
F-12-398.8	Dolomite	6,385	2.61	546	884	4.99	2.48	42	358	2.5
F-14-227.8	Dolomite	10,551	4.64	750	1,060	2.58	2.57	50	530	2.0
F-14-230.35	Dolomite	13,429	4.80	750	1,060	2.51	2.57	55	530	2.0
F-14-295.8	Dolomite	4,977	2.91	530	970	3.32	2.48	47	540	1.8
F-14-298.7	Dolomite	9,047	3.44	530	970	2.27	2.48	44	540	1.8
F-14-313.3	Dolomite	10,919	4.44	820	1,270	2.20	2.63	52	380	3.3
F-14-315.55	Dolomite	10,855	4.18	820	1,270	2.76	2.63	51	380	3.3
F-15-334.65	Dolomite	17,885	10.08	1,230	1,920	0.11	2.76	72	640	3.0

TABLE B-5 (continued)

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso-tropy
F-15-365.4	Dolomite	13,246	9.76	650	660	1.51	2.63	58	530	1.2
F-15-389.55	Dolomite	13,411	3.96	1,140	1,940	1.32	2.70	60	990	2.0
F-15-413.3	Dolomite	10,301	4.10	750	990	1.46	2.74	64	520	1.9
F-15-436	Dolomite	12,096	5.71	820	1,560	1.16	2.71	60	480	3.3
F-15-449.05	Dolomite	8,933	4.01	680	880	1.62	2.66	60	640	1.4
F-15-456.3	Dolomite	6,469	3.39	540	1190	2.26	2.71	62	640	1.9
F-16-203.85	Dolomite	6,582	5.60	850		2.15	2.61	66	690	
F-16-236.75	Dolomite	20,212	4.06	1,320	2,450	0.10	2.67	60	650	3.8
F-16-265.55	Dolomite	13,970	9.66	890	2,150	0.51	2.65	48	580	3.7
F-16-278.75	Dolomite	13,110	7.25	1,180	1,670	0.24	2.65	53	670	2.5
F-16-284.15	Dolomite	14,365	8.39	1,040	1,850	0.18	2.73	55	550	3.4
F-16-292.95	Dolomite	12,046	4.40	940	1,360	0.72	2.63	63	610	2.2
F-16-294.65	Dolomite	5,377	3.21	940	1,360	3.35	2.67	63	610	2.2
F-17-180.2	Dolomite	7,645	10.77	654	964	1.07	2.67	60	502	1.9
F-17-199.0	Dolomite			810	1,440		2.62		612	2.4
F-17-202.4	Dolomite	10,888	7.43	1,324	2,186	0.54	2.73	46	1,054	2.1
F-17-207.0	Dolomite	8,057	10.07	463		0.53	2.54	58	760	
F-17-215.7	Dolomite	15,622	4.61			0.68		64		
F-17-230.8	Dolomite	7,844	9.40	898	1,196	0.59	2.62	64	492	2.4
F-17-260.7	Dolomite	11,018	3.62	930	2,543	0.80	2.70	61	522	4.9
	Average	10,034	5.62	841	1,428	1.58	2.65	57	538	2.9
	Maximum	20,212	14.05	1,432	2,911	4.99	2.78	81	1,054	8.6
	Minimum	2,436	1.79	401	660	0.10	2.44	37	171	1.1
F-10-280.6	Limestone	16,876	16.40	998	2,127	0.58	2.70	57	854	2.5
F-10-300.25	Limestone	14,484	10.80	998	2,118	0.99	2.70	44	571	3.7
F-10-309.55	Limestone	14,578	11.90			0.62	2.66	45		
F-10-311.1	Limestone	20,673	12.90	1,280	2,069	0.22		56	626	3.3
F-10-327.05	Limestone	15,622	4.93	1,091	1,866	1.00	2.65	42	403	4.6
F-10-345.3	Limestone	14,656	13.40	1,080	1,688	1.30	2.61	47	589	2.9
	Average	16,148	11.72	1,089	1,974	0.79	2.66	49	609	3.4
	Maximum	20,673	16.40	1,280	2,127	1.30	2.70	57	854	4.6
	Minimum	14,484	4.93	998	1,688	0.22	2.61	42	403	2.5

TABLE B-6 ISGS geotechnical data for samples from the Dunleith Formation (Ordovician, Galena Group) in the SSC study area.

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso-tropy
F-5-394.4	Dolomite	3,527	2.49	709	743	3.60	2.47	39	241	3.1
F-5-400	Dolomite	6,402	8.36	583	1,281	4.01	2.54	42	350	3.7
F-5-412.2	Dolomite	6,202	3.58	693	1,409	1.80	2.51	39	574	2.5
F-5-437	Dolomite	12,642	3.72	1,086	1,591	1.20	2.76	47	614	2.6
F-7-372.4	Dolomite	8,668	3.62	660	1,007	1.57	2.68	60		
F-7-381.2	Dolomite	9,046	4.52	411	1,204	0.63	2.64	60	473	2.5
F-7-391.6	Dolomite	11,264	4.27	845	1,221	1.84	2.61	56	585	2.1
F-9-400.5	Dolomite	5,484	8.21	424	721	3.07	2.43	54	293	2.5
F-9-405.5	Dolomite	8,569	4.03	400	650	2.57	2.47	51	328	·2.0
F-9-420.8	Dolomite	9,590	3.33	698	801	1.65	2.59	60	362	2.2
F-9-435.2	Dolomite	6,908	8.10	730	1,201	1.62	2.62	55	206	5.8
F-9-451.4	Dolomite	8,515	5.96	852	1,095	1.96	2.51	43	411	2.7
F-9-467.5	Dolomite	13,000	3.80	726	896	1.61	2.68	55	766	1.2
F-9-475	Dolomite	13,591	3.16	592	1,370	0.44	2.69	55	592	2.3
F-9-492.4	Dolomite	7,650	11.45	585	1,388	2.86	2.42	41	571	2.4
F-11-250.4	Dolomite	1,367	1.84	283	1,166	6.02	2.53	36		
F-11-259.75	Dolomite	1,705	1.39	168	592	10.21	2.39	36	193	3.1
F-11-266.8	Dolomite	1,927	1.44	169	231	6.62	2.38	36	117	2.0
F-12-409.45	Dolomite	7,773	3.54	549	896	4.97	2.46	44	279	3.2
F-12-417.7	Dolomite	6,589	7.40	497	730	3.87	2.47	50		
F-12-442.15	Dolomite	5,702	3.12	544	528	5.18	2.49	44	282	1.9
F-14-359.3	Dolomite	5,654	2.72	480	830	2.97	2.59	40	370	2.2
F-14-388.05	Dolomite	4,079	1.33	550	880	2.33	2.55	49	320	2.8
F-14-391.45	Dolomite	9,486	4.11	550	880	1.72	2.55	48	320	2.8
F-16-311.5	Dolomite	7,326	3.30	1,111	1,146	2.42	2.62	68		
F-17-284.4	Dolomite	11,774	3.80	1,254		0.47	2.69	66	697	
F-17-289.8	Dolomite	10,760	14.36	996	1,524	0.83	2.71	54	450	3.4
	Average	7,600	4.70	635	999	2.89	2.56	49	408	2.7
	Maximum	13,591	14.36	1,254	1,591	10.21	2.76	68	766	5.8
	Minimum	1,367	1.33	168	231	0.44	2.38	36	117	1.2

TABLE B-7 ISGS geotechnical data for samples from the Platteville (Ordovician) in the SSC study area.

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso-tropy
F-5-443	Dolomite	11,803	11.77	926	1,540	3.09	2.57	50	364	4.2
F-5-449.6	Dolomite	9,287	3.93	665	1,360	3.30	2.44	49	695	2.0
F-5-460.2	Dolomite	9,696	3.98	914	1,457	1.20	2.67	49	434	3.4
F-11-290.3	Dolomite	12,154	4.06	1,451	2,137	2.08	2.69	54	1,039	2.1
F-11-306.6	Dolomite	10,855	5.99	1,080	1,314	1.26	2.62	58	511	2.6
F-11-325.7	Dolomite	11,783	4.09	407	1,026	0.66	2.68	78	417	2.5
F-11-342.75	Dolomite	10,372	13.88	963	2,278	2.00	2.66	69	1,072	2.1
F-11-344.4	Dolomite	7,243	16.05	678	1,700	1.32	2.71	64	678	2.5
F-11-432.6	Dolomite	12,835	4.02	1,572	1,292	1.10	2.69	61	998	1.3
F-12-459.45	Dolomite	9,663	4.66	813		3.50	2.47	45		
F-12-469.55	Dolomite	10,512	3.20	976		2.09	2.51	42		
F-12-482.2	Dolomite	9,961	3.41	739	1,338	3.27	2.56	33	488	2.7
F-14-405.2	Dolomite	15,278	4.74	1,130	1,580	1.50	2.66	52	820	1.9
F-14-407.85	Dolomite	18,149	4.94	1,130	1,580	1.51	2.66	55	820	1.9
F-14-438.9	Dolomite	12,775	4.21	1,460	1,400	1.85	2.65	51		
F-14-442.4	Dolomite	11,822	4.17	1,100		2.17	2.65	57	420	
F-14-448.2	Dolomite									
F-17-319.6	Dolomite	15,710	9.90	1,445		0.13	2.76	64	1,176	
F-17-322.2	Dolomite	15,965	6.20	1,230	2,289	0.04	2.71	70	958	2.4
F-17-341.6	Dolomite	13,290	4.01	887		0.32	2.73	69	887	
F-17-446.9	Dolomite	14,227	13.86	1,120	1,717	0.09	2.70	66	923	1.9
	Average	12,169	6.55	1,034	1,601	1.62	2.64	57	747	2.4
	Maximum	18,149	16.05	1,572	2,289	3.50	2.76	78	1,176	4.2
	Minimum	7,243	3.20	407	1,026	0.04	2.44	33	364	1.3
F-11-383.6	Limestone	22,090	10.89	1,164	2,130	0.39	2.67	60	667	3.2
F-11-393.4	Limestone	25,736	4.19	1,313	3,017	0.12	2.70	58	797	3.8
F-11-396.55	Limestone	20,498	3.82	1,756	2,234	0.22	2.71	56	682	3.3
	Average	22,775	6.30	1,411	2,460	0.24	2.69	58	715	3.4
	Maximum	25,736	10.89	1,756	3,017	0.39	2.71	60	797	3.8
	Minimum	20,498	3.82	1,164	2,130	0.12	2.67	56	667	3.2

TABLE B-8 ISGS geotechnical data for samples from the St. Peter Sandstone (Ordovician, Ancell Group) in the SSC study area.

Borehole & Depth	Rock Type	Unconfined Compressive Strength (PSI)	Modulus PSIx10*6	Indirect Tensile Strength (PSI)	Axial Point Load Index (PSI)	Moisture Content (%)	Specific Gravity	Shore Hardness	Diam. Point Load Index (PSI)	Index Of Aniso-tropy
F-17-466.9	Sandstone	3,163	1.33	177	373	7.10	2.24	20	96	3.9
F-17-513.0	Sandstone	1,300	0.52	170	334	7.10	2.21	9	73	4.6
F-17-569.3	Sandstone	1,438	0.42	90	256	7.47	2.25	10	43	6.0
F-17-629.3	Sandstone	1,279	0.48	41	78	4.82	2.22	10	21	3.7
	Average	1,795	0.69	120	260	6.62	2.23	12	58	4.5
	Maximum	3,163	1.33	177	373	7.47	2.25	20	96	6.0
	Minimum	1,279	0.42	41	78	4.82	2.21	9	21	3.7